Sedimentology and Stratigraphy of the Lower Silurian Grimsby Formation, in subsurface, Lake Erie and southwestern Ontario

BY

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ABSTRACT

Since the first offshore Lake Erie well was drilled in 1941, the Grimsby and Thorold formations of the Cataract Group have been economically important to the oil and gas industry of Ontario. The Cataract Group provides a significant amount of Ontario's gas production primarily from wells located on Lake Erie.

The Grimsby - Thorold formations are the result of nearshore estuarine processes influenced by tides on a prograding shelf and are composed of subtidal channel complexes, discrete tidal channels, mud flats and non-marine deposits. Deposition was related to a regressive - transgressive cycle associated with eustatic sea level changes caused by the melting and resurgence of continental glaciation centred in Africa in the Late Ordovician/Early Silurian. Grimsby deposition began during a regression with the deposition of subtidal channel complexes incised into the marine deposits of the Cabot Head Formation. The presence of mud drapes and mud couplets suggest that these deposits were influenced by tides. These deposits dominate the lower half of the Grimsby. Deposition continued with a change from these subtidal channel complexes to laterally migrating, discrete, shallow tidal channels and mud flats. These were in turn overlain by the non-marine deposits of the Thorold Formation. Grimsby - Thorold deposition ended with a major transgression replacing siliciclastic deposition with primarily carbonate deposition.

Sediment was sourced from the east and southeast and associated with a continuation of the Taconic Orogeny into the Early Silurian. The fluvial head of the estuary prograded from a shoreline that was located in western New York and western Pennsylvania running NNE-SSW and then turning NW-SE and paralleling the present day Lake Erie shoreline.

The facies attributed to the Grimsby - Thorold formations can be ascribed to the three zones within the tripartite zonation suggested by Dalrymple *et al.* (1992) for estuaries, that is, a marine-dominated facies, a mixed energy facies, and a facies that is dominated by fluvial processes. Also, sediments within the Grimsby - Thorold are commonly fining upwards sequences which are common in estuarine settings whereas deltaic deposits are normally composed of coarsening upwards sequences in a vertical wedge shape with coarser material near the head. The only coarsening observed was in the Thorold Formation and attributed to non-marine deposition by palynological evidence.

The presence of a lag deposit at the base of the sediments of the Grimsby - Thorold formations suggests that they were incised into the Cabot Head Formation. Further, the thickness of Early Silurian sediments located between the top of the Queenston Formation, where Early Silurian sedimentation began, to the top of the Reynales - Irondequoit formation are constant whether the Grimsby - Thorold formations are present or not. Also, cross-sections using a sand body located in the Cabot Head Formation for correlation further imply that the Grimsby Formation has been incised into the previous deposits of the Cabot Head.

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TABLE OF CONTENTS

Abstract	ii
Acknowledgements	iv
Table of contents	vi
List of figures	viii
List of tables	xiv
Introduction	1
Lake Erie and the oil industry	3
Methods of data collection	7
Well files	7
Geophysical well logs	10
Cores	15
Cross Sections and Database	17
Maps	21
Problems encountered during data collection	22
Regional Geological Setting	28
Regional Geologic History	28
Cyclicity in the Appalachian Foreland Basin	33
Geology of the Cataract Group and Associated formations	39
Trace fossils and the Cataract Group	49
Paleopalynology and the Cataract Group	50
Facies observations	51
Facies A	51
Facies B	55
Facies C	64
Facies D	73
Facies E	77
Facies in well logs	77
Palynological observations	85

Interpretation of observations 89

Facies interpretations 89
Facies A 89
Facies B 92
Facies C 93
Facies D 94
Facies E 95

Geometry of Grimsby - Thorold formations 98

Paleoenvironment of the Grimsby - Thorold formations 105

Conclusion 111

Further work 112

References 114

Appendix 'A' - Core Sections 129

LIST OF FIGURES

No.	Description of Figure	Pg.
1	Location of study area.	4
2	Illustration of the block, tract, and quarter system used for well locations on Lake Erie.	9
3	Core section illustrating the effectiveness of the 100 API units cutoff for determining 'clean' sand	12
4	Full well log suite from Consumers 13526A, 98-B	14
5	Example of core section drawing	16
6	Portion of compiled database	18
7	Representative formation boundary picks from wells in several areas on Lake Erie	20
8	Well log which does not include Queenston - Whirlpool formation boundary	23
9	A neutron calibrator log	24
10a	Well log from well drilled in 1961 illustrating a very unusual presentation	25
10b	Well log from well drilled in 1962 illustrating a 1:600 scale presentation	26
11	Important basins and arches of the Great Lakes region	29
12	Location of study area in relation to reported areas of Late Ordovician - Early Silurian glaciation	34
13	Sea level curves showing relative changes of water depth on the North American platform	37
14	Curves of Vail et al. (1977) depicting first and second order global cycles of relative change of sea level	38
15	Map of tidal channels and estuaries along the sandy intertidal flats of the German Bay, North Sea	48
16	Consumers 13169, Block 99-K, illustrating Facies A	53
17	Common hematitic, fossiliferous bed from Consumers 13224, Block 121-A	54
18	An unoxidized, non-hematitic fossiliferous bed from Consumers 13224, Block 121-A	54
19	Dish structures common to sand body in Facies A, Consumers 13221, Block 123-O	56
20	Hummocky cross-stratification in sand body, Consumers 13169, Block 99-K	57

No.	Description of Figure	Pg.
21	Facies B, Consumers 13224, Block 121-A	58
22	Common lag deposit at base of Facies B, Consumers 13197, Block 153-H	59
23a	Mud couplets observed in Facies B, Consumers 13197, Block 153-H	61
23b	Mud couplets observed in Facies B, Consumers 13197, Block 153-H	61
24	Consumers 13153, Block 122-J, showing Facies B	62
25	Consumers 13237, Block 123-F, illustrating several lag deposits near the base of Facies B	63
26	Common appearance of Facies C, Consumers 13164, Block 157-M	65
27a	Pembina #2A, Block 68-Q, illustrating a 'normal' Facies C succession	66
27b	Consumers 13167, Block 152-N, illustrating an abnormally thick Facies C succession	67
28	Example of ripple cross-stratification from Facies C in Consumers 13153, Block 122-J	68
29a	Consumers 13214, Block 122-L, illustrating a sandy Facies C	69
29b	Consumers 13232, Block 155-W, illustrating a sandy Facies C	70
30a	Consumers 13228, Block 122-T, illustrating a shaly Facies C	71
30b	Consumers 13094, Block 124-C, illustrating a shaly Facies C	72
31	Facies D, Consumers 13170, Block 94-M	74
32a	Rippled cross-stratification from Facies D, Consumers 13167, Block 152-N	75
32b	Rippled cross-stratification from Facies D, Consumers 13167, Block 152-N	75
32c	Rippled cross-stratification from Facies D, Consumers 13167, Block 152-N	75
33a	Heavily bioturbated Facies D from Consumers 13197, Block 153-H	76
33b	Heavily bioturbated Facies D from Consumers 13197, Block 153-H	76
34	*Teichichnus* burrow in Facies D, Consumers 13170, Block 94-M	76
35	Boundary between Facies D and Facies E, Consumers 13153, Block 122-J	78
36	Well log appearance for facies, Consumers 13202, Block 155-F	79
37	Well log appearance for facies, Pembina #1 Lake Erie, Block 43-H	80

No.	Description of Figure	Pg.
38	Well log appearance for facies, Consumers 13223, Block 154-G	81
39	Well log appearance for facies, Pembina #1 Lake Erie, Block 89-L	83
40	Well log appearance for facies, Pembina #1 Lake Erie, Block 68-L	84
41	Cross-section illustrating Grimsby Formation incising into Cabot Head Formation using the Cabot Head sand body	101
42	Schematic of tide-dominated estuaries	108
	Appendix: Core Sections	129
43	Legend	130
44	Anschutz, Block 8-V, pt. 1	131
45	Anschutz, Block 8-V, pt. 2	132
46	Long Point Port Dover #1, Block 14-S	133
47	Long Point Port Dover #4, Block 14-U	134
48	Place Anschutz, Block 19-L	135
49	Anschutz, Block 20-D	136
50	Anschutz, Block 21-W	137
51	Anschutz, Block 23-S	138
52	Pembina #3, Block 39-W	139
53	Pembina #2, Block 41-J	140
54	Pembina #3, Block 41-P	141
55	Pembina #2, Block 42-F	142
56	Mitchell 750-56, Block 44-S, pt. 1	143
57	Mitchell 750-56, Block 44-S, pt. 2	144
58	Mitchell 623-26, Block 45-N	145
59	Consumers 13315, Block 56-R	146
60	Consumers 13316, Block 57-V	147
61	Pembina #4, Block 62-T	148

No.	Description of Figure	Pg.
62	CWP 68-5, Block 63-G	149
63	Pembina #4, Block 64-S	150
64	Pembina #2, Block 65-E	151
65	Pembina #4, Block 67-F	152
66	Pembina #2A, Block 68-Q	153
67	Pembina #1, Block 69-Q	154
68	Pembina #2, Block 70-G, pt. 1	155
69	Pembina #2, Block 70-G, pt. 2	156
70	Pembina #4, Block 89-K	157
71	Pembina #4, Block 91-S	158
72	Consumers Pan Am 13047, Block 93-W	159
73	Consumers 13300, Block 94-K	160
74	Consumers 13170, Block 94-M	161
75	Consumers 13321, Block 95-K	162
76	Consumers 13148, Block 96-V	163
77	Consumers 13059, Block 97-P	164
78	Consumers 13081, Block 98-P	165
79	Consumers 13097, Block 98-Y	166
80	Consumers 13169, Block 99-K	167
81	Consumers 13034, Block 100-I	168
82	Consumers 13035, Block 101-K	169
83	Consumers 13038, Block 102-B	170
84	Consumers 13036, Block 118-M	171
85	Consumers 13053, Block 119-A	172
86	Consumers 13112, Block 119-P	173
87	Consumers 13013, Block 120-S	174

No.	Description of Figure	Pg.
88	Consumers 13224, Block 121-A	175
89	Consumers 13229, Block 122-A	176
90	Consumers 13198, Block 122-A	177
91	Consumers 13151, Block 122-H	178
92	Consumers 13152, Block 122-I	179
93	Consumers 13153, Block 122-J	180
94	Consumers 13214, Block 122-L	181
95	Consumers 13228, Block 122-T	182
96	Consumers 13237, Block 123-F	183
97	Consumers 13147, Block 123-H	184
98	Consumers 13221, Block 123-O	185
99	Consumers 13044, Block 123-Q	186
100	Consumers 13089, Block 123-T	187
101	Consumers 13094, Block 124-C	188
102	Consumers 13117, Block 124-G	189
103	Consumers 13132, Block 124-G	190
104	Consumers 13154, Block 124-N	191
105	Consumers 13329, Block 125-F	192
106	Telesis 13926, Block 126-A	193
107	CPOG Haldimand #1, Block 131-G	194
108	Consumers 13185, Block 152-B	195
109	Consumers 13167, Block 152-N	196
110	Consumers 13197, Block 153-H	197
111	Consumers 13223, Block 154-G	198
112	Consumers 13226, Block 155-A	199

No.	Description of Figure	Pg.
113	Consumers 13202, Block 155-F	200
114	Consumers 13234, Block 155-I	201
115	Consumers 13222, Block 155-P	202
116	Consumers 13298, Block 155-P	203
117	Consumers 13299, Block 155-P	204
118	Consumers 13232, Block 155-W	205
119	Consumers 13204, Block 156-L	206
120	Consumers 13240, Block 156-X	207
121	Consumers 13164, Block 157-M	208
122	Consumers 13275, Block 158-D	209
123	Consumers 13273, Block 158-K	210
124	Anschutz #4, Block 162-T	211
125	Consumers 13171, Block 185-C	212
126	Consumers 13747, Block 186-J	213
127	Consumers 13041, Block 187-D	214
128	Consumers 13755, Block 220-W	215
129	Shawnee UBR South Walsingham, Norfolk County, Tract 3/Lot 4/Conc A	216
130	Shawnee UBR South Walsingham, Norfolk County, Tract 3/Lot 5/Conc I	217
131	Shawnee UBR North Walsingham, Norfolk County, Tract 1/Lot 10/Conc VII	218

LIST OF TABLES

No.	Description of Table	Pg.
1	Active and suspended wells for Lake Erie pools, 1988	6
2	Cumulative Lake Erie gas production by pool for 1992	6
3	Stratigraphic column correlating Virginia, Maryland, Pennsylvania, central and western New York, the Niagara Peninsula and eastern Lake Erie, southwestern Ontario, Ohio, and Michigan	31
4	Summary of samples submitted for palynological analyses	87
5	Summary of identified palynomorphs from samples WGP8, WGP7 and WGP2	88
6	Summary of observations and interpretations of defined facies	97

INTRODUCTION

The Grimsby Formation, Early to Middle Silurian (Llandoverian), is the uppermost formation of the Cataract Group in southern Ontario and is an economically important reservoir for hydrocarbons in southern Ontario. Hydrocarbon production is primarily gas, and is largely derived from beneath Lake Erie and adjacent lands.

Bounded below by the sandstone and shale of the Cabot Head Formation and above by the Thorold Sandstone, the Grimsby Formation is dominated by fine-grained to very fine-grained, quartzose sandstone with minor siltstone and mudstone; its colour varies locally and may be red, pale green or mottled gray. The Grimsby is exposed in outcrop along the Niagara Escarpment, from Ancaster to western New York State, and along the Niagara Gorge. In subsurface, the formation occurs throughout the Niagara Peninsula, eastern Lake Erie and extends approximately as far west as offshore of Rondeau Harbour. The Grimsby is thickest to the south and east (up to approximately 24 m in Canada) and pinches out to the north and west (Sanford, 1969). The formation correlates with the fluvial quartz arenites and interbedded shales of the Tuscarora Formation to the south and southeast in central Pennsylvania and northeastern Ohio (Yeakel, 1962; Cotter, 1983) where it is also an important hydrocarbon producer. It also correlates with the lower portion of the Shawangunk Conglomerate of southeastern New York and eastern Pennsylvania as well as the undifferentiated Albion Series of northern West Virginia.

While the Grimsby Formation is an economically important zone of hydrocarbon production, no detailed regional studies of the sedimentology and facies of the formation, in subsurface, have been published. Most studies have focused on relatively limited outcrop along the Niagara Escarpment and into New York State. In contrast, a wealth of data, as core, drill cuttings and geophysical well logs, are available for the vast subcrop belt of the Grimsby Formation in Ontario but have been little-studied in terms of facies.

This study was funded by Pembina Resources Ltd. and Telesis Oil and Gas Ltd. (which was purchased by Pembina Resources Ltd. over the course of this study) with matching funds from NSERC Industrially-Oriented Research Grants Program. The funding was provided on agreement that this thesis produce specific materials for the company, including an extensive data base of formation picks and digitized well logs. In addition to this large resource that was not included in this thesis, the study describes the regional geology and sedimentology of the Grimsby and Thorold formations in sufficient detail so as to allow a first order interpretation of the depositional environments and history of the deposits. Further detail was beyond the scope of this thesis.

Core and geophysical-logs were used to conduct a modern study of the sedimentology and facies of the Grimsby Formation in subsurface. The specific results of the study include detailed descriptions and interpretations of the sedimentology and facies in subcrop and regional maps and correlation charts showing the distribution of a variety of aspects of the formation (isopachs of the formation, structure contour maps, and important surfaces within the formation). The project also rendered an extensive database of consistent formation boundary picks for the Grimsby, Cabot Head, and Thorold formations and a set of digitized well logs from all wells penetrating the Grimsby Formation beneath Lake Erie.

The study area (Figure 1) was confined to the subsurface of Lake Erie and directly adjacent lands where the Grimsby Formation is present in subcrop, generally the west-central to eastern portions of the lake. To aid in identifying lateral lithologic variations, wells bordering the Grimsby subcrop area, but lacking Grimsby Formation, were also

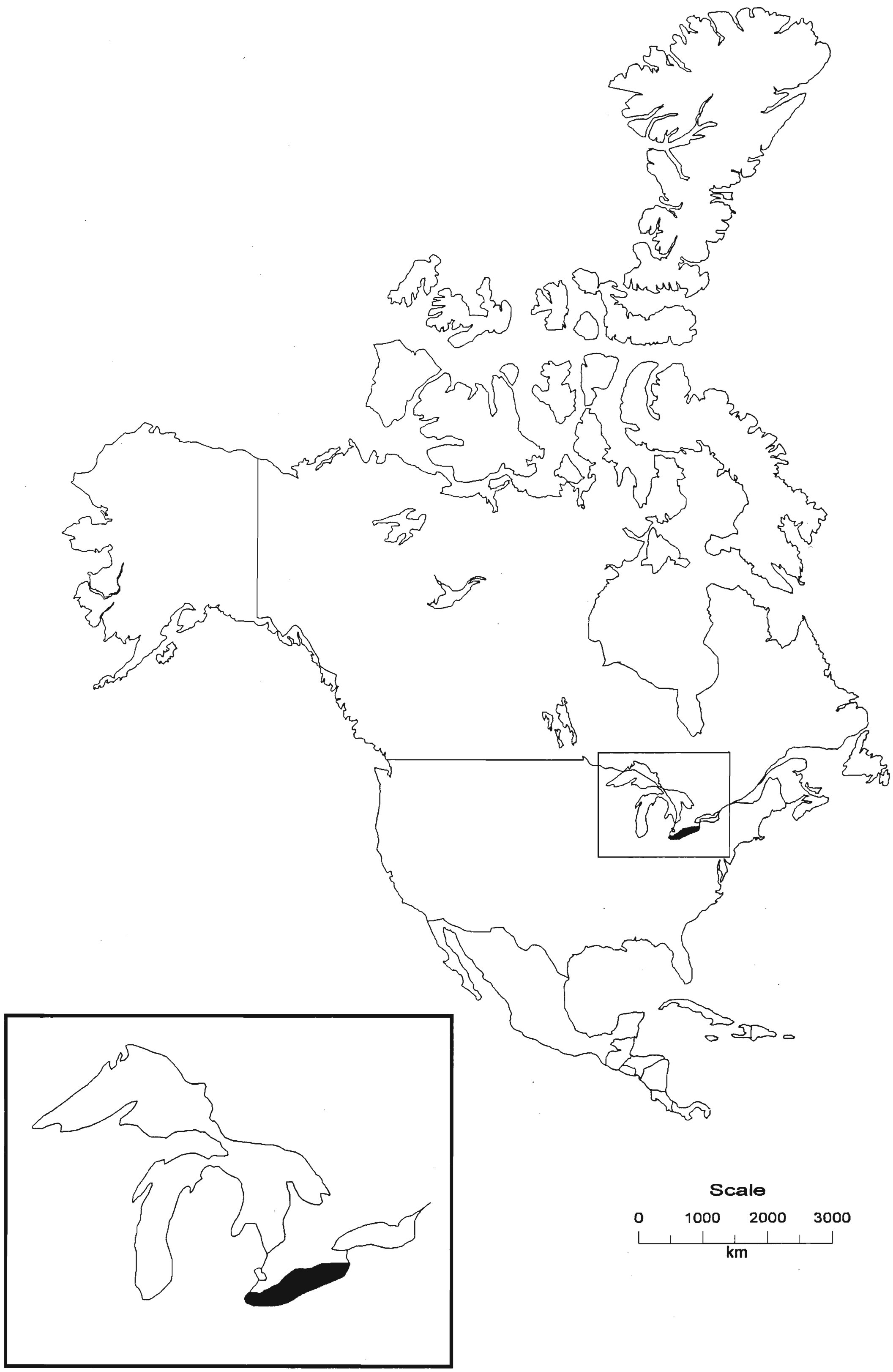


Figure 1: Location of study area. Wells and cores for study were primarily from Lake Erie. Boxed area highlights Lake Erie (dark area) in relation to the other Great Lakes.

included. The study area is extensively drilled with approximately 1200 wells, most penetrating the Cataract Group and the top of the Queenston Formation. Each well has at least one geophysical log and most have several logs to aid in identifying formation boundaries and lithologic changes in subsurface.

LAKE ERIE AND THE OIL INDUSTRY

Since 1941, when the first offshore well was drilled, Lake Erie and the Cataract Group have been very important to Ontario's oil and natural gas industry. Although small by world standards, the Cataract Group provides a significant amount of Ontario's natural gas production (55% of Ontario's total gas production; T. Carter, pers. comm) with most of the production coming from beneath Lake Erie. The Middle Silurian Guelph Formation, A-1 Carbonate, and A-2 Carbonate also produce gas from beneath Lake Erie but in lesser amounts than the Cataract Group. By law, only natural gas can be produced from wells drilled on Lake Erie and absolutely no oil production is allowed. As a result of this regulation, several possible oil wells scattered throughout the lake have been plugged.

As of 1988 (the latest figures available), there were 628 active, producing gas wells on the lake with 117 suspended wells (Table 1). The 628 producing wells make up over half of the 1220 producing gas wells in Ontario. Within the Cataract Group, the primary producing zone is the Grimsby Formation but significant amounts of gas are produced from the Thorold Sandstone and Whirlpool Formation, as well as rare production zones within isolated sandstones from the Cabot Head Formation. Total Lake Erie gas production for that year was over 383,000,000m^3 (~13.5BCF), representing about 76% of the total gas production for all of Ontario. Lake Erie gas production is divided into various 'pools' representing a different geographical area or differing production zones (Table 2). For 1994, Ontario's gas consumption was about 24.3 billion

m^3 (860BCF), the bulk of which is produced and transported from western Canada, with Ontario production providing approximately 2% of the total gas consumed (T. Carter, pers. comm.).

POOL NAME	ACTIVE WELLS	SUSPENDED WELLS	PRODUCTION 1988 $1000m^3$
Clear Creek	79	24	58486.9
D'Clute	10	3	1478.4
Dover	51	8	10445.7
Leepfrog	8	4	6672.1
Maitland	237	11	119612.6
Morpeth	26	9	108618.1
Selkirk	83	11	13577.1
Silver Creek	69	37	52578.9
Tilbury	65	10	12102.0
Lake Erie Totals	**628**	**117**	**383571.8**
% of Ontario Total			**76.2%**

Table 1: Active and suspended wells for Lake Erie pools including production levels as of 1988 (latest figures available; modified from Carter, 1992).

POOL NAME	DISCOVERY DATE	DEPTH (m)	PRODUCING FORMATION(S)	CUM. GAS PROD. ($1000m^3$)
Clear Creek	1959	500	Reynales, Thorold, Grimsby, Cabot Head, Whirlpool	805514.2
D'Clute	1957	440	A-1 & A-2 Carbonate, Guelph	240238.9
Dover	1959	366	Thorold, Grimsby, Cabot Head, Whirlpool, Reynales, Irondequoit	426074.4
Various undifferentiated production units			Lower Silurian sandstone	94065.0
Leepfrog	1965	328	Grimsby, Whirlpool, Cabot Head	220831.1
Maitland	1959	300	Thorold, Grimsby, Whirlpool, Cabot Head	1714070.7
Morpeth	1972	517	Guelph	1201118.2
Selkirk	1958	442	Thorold, Grimsby, Reynales, Irondequoit, Whirlpool	556780.8
Silver Creek (reef)	1968	404	Guelph	698584.8
Silver Creek (sand)	1968	535	Thorold, Grimsby, Reynales	428993.0
Tilbury (includes land production)	1906	375	A-1 & A-2 Carbonate, Guelph	7729925.0
Total Lake Erie Gas Production				**14116196.1**

Table 2: Cumulative Lake Erie gas production by pool for 1992 (latest figures available). Producing formations are also listed along with the pool discovery date (Carter *et al.*, 1995).

METHODS OF DATA COLLECTION

Data were collected from two primary sources: 1) geophysical well logs, and 2) drill cores. Subsurface data (geophysical well logs, cores, well files) were primarily located at the Ontario Petroleum Resources Laboratory, operated by the Ontario Ministry of Natural Resources, in London, Ontario.

WELL FILES

Files are available for each drilled well in Ontario, approximately 11,000 in total. Each well file includes:

1) the Well File Card, which is essentially a summary sheet of the well's location, name and permit number, the well operator, spud and rig release dates, all essential elevations (e.g., KB elevation), the well formation picks, either by the operator or the Ministry of Natural Resources, drill stem tests, gas and oil shows, completions, and the final status of the well;
2) a Form 107, which includes the complete well summary from spud to completion including much of the information available on the Well File Cards as well as drill stem test intervals and results, completion data (e.g., the interval, type of completion, and further well workovers);
3) copies of geophysical well logs; the availibility of well logs is dependent upon the operator because there is no regulation requiring geophysical logging of a drilled well in Ontario;
4) other data, including core analyses, drill stem test reports along with water, oil and gas analyses, completion reports, location surveys, and various correspondence about the well.

The files for wells on land are arranged in alphabetical order by county, and then by township, lot, tract, and concession. In contrast, Lake Erie is slightly different as it is divided into blocks, tracts and quarters (see Figure 2 for full explanation). Each block is five minutes of longitude in width and five minutes of latitude in height. Blocks number from 1 to 480 and begin in the far east end of the lake at the Niagara River and continue sequentially westward along the northern shoreline and then reverse until they reach the southeastern shoreline once again. They reverse again and upon reaching shorelines, reverse until the entire lake on both sides of the border has been blocked. Each block is subdivided into twenty five tracts of one minute longitude by one minute of latitude creating a grid of five by five tracts. These are denoted by the letters A through Y with A being in the upper right corner and are lettered sequentially beginning at that point. They continue west for five tracts within a block and then reverse, and are then lettered sequentially eastward, reversing again and so on until Y tract which is located in the lower left corner of a block. Each tract is quartered with the quarters numbered counterclockwise beginning with 1 in the upper right corner.

The content of well files depend on the operator sending the information to the Petroleum Resources Laboratory. In many cases, drill stem tests, fluid analyses, and completions were performed but such information is not available in the well files because the operator did not send them to the laboratory. In many cases, especially for older wells, the well operators no longer exist, having been bought out, merged with another company, or have simply ceased operating. The well information has therefore been lost. For more recent wells, the only information that is required by the Ontario government is the completion of Form 107. Generally speaking, the older the well, the less complete the file. The technology available to well operators prior to about 1960 was limited and many well files contain only a Well File Card. In recent years, well files are more complete as geophysical well logs and other sources of information have become widely accepted.

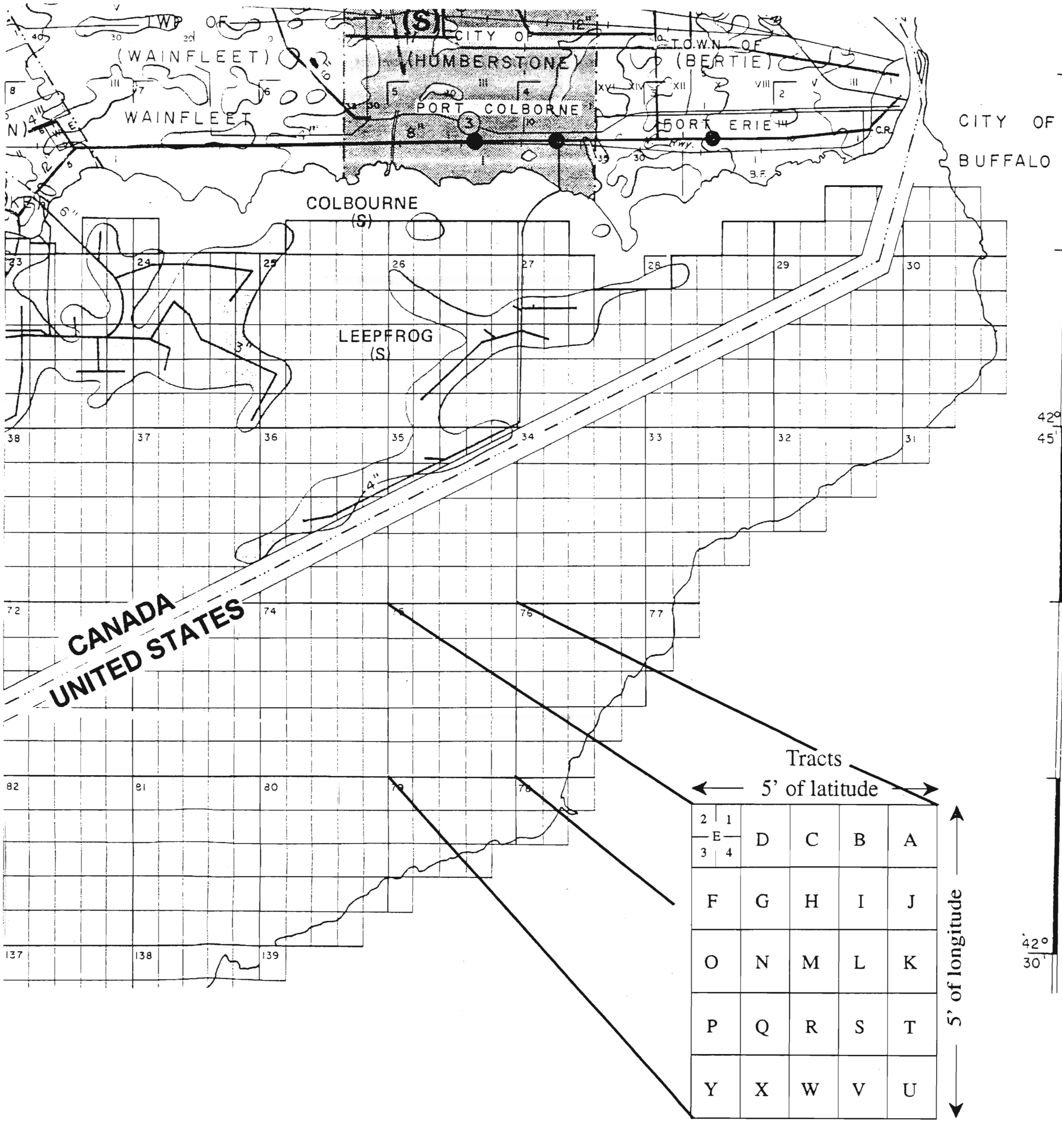


Figure 2: Illustration of the block, tract, and quarter system used for well locations on Lake Erie. Figure shows a portion of eastern Lake Erie where block numbering begins (above). Dashed line is international border. Blocks are five minutes of longitude by five minutes of latitude in size and are numbered from 1 through 480 sequentially from the Niagara River ignoring the international border, and delineating the entire lake. The numbering sequence follows the north shore to the west, then reverses to the east reaching the southeast shoreline where it reverses once again and so on. Blocks are divided into twenty five tracts of one minute of longitude by one minute of latitude (right). Tracts are further subdivided as shown (modified from Booth-Horst, 1982).

GEOPHYSICAL WELL LOGS

The well files for Lake Erie are generally more complete than for those drilled on land, primarily due to the limited number of operators and the various regulations that govern drilling on the lake. Therefore, geophysical well logs are available for virtually every well. The present study included 1194 wells with geophysical well logs. The primary well log used was the gamma ray log, a measure of the natural radioactivity of the rock which is closely related to the potassium, thorium, and uranium content of the formation (e.g., Cant, 1984). The gamma ray log is a good indicator of basic lithology (eg., sand versus shale), as these elements are most common in shales but largely absent in sands. In terrigenous clastic successions the log reflects the 'cleanness' (lack of clays) or shaliness (high radioactivity on the API scale) of the rock, averaged over an interval of about 2m (Cant, 1992). Because of this property, gamma ray log patterns mimic vertical sand-content trends of facies successions. Although the gamma ray reading is not a function of grain size and is a reading of radioactive elements common to most clays, one can still ascertain vertical grain size trends. The log was utilized in this study to ascertain fining and coarsening sequences as well as the thickness of sand for the Grimsby Formation. In the case of the Cataract Group, the gamma ray scale is commonly 0 - 200 and 200 - 400 API units.

The response of the gamma ray tool is non-linear so a cutoff halfway between the scale end markers (100 API units) would indicate a value of 30 per cent shale (Cant, 1992). In this study, to determine the sand thickness, a value of under 100 API units was considered a 'clean' sand and a value over 100 API units was considered a shale (Figure 3). Because of the variability of the curves from well to well and the non-continuous expression of the sands within each well, any portions of the curve which went below 100

API units was considered a 'clean' sand. For each well, the thicknesses of all the 'clean' sand zones were added and a total sand thickness was established. The total sand thickness was then used to aid in ascertaining trends within the Grimsby and Thorold formations. The gamma ray log was also the primary source in determining formation contacts to develop a database used for contouring maps.

Other well logs, such as the dual induction lateralog and the compensated neutron-density logs, were also used in this study. Dual induction lateralogs (or resistivity) logs are a series of curves measuring the shallow, intermediate, and deep resistivity of interstitial formation fluids to the flow of electric current, either transmitted directly to the rock through an electrode, or magnetically induced deeper into the formation from the hole as in the case of the dual induction lateralog (Cant, 1992). The terms shallow, intermediate, and deep refers to the horizontal distance from the well bore to the deepest penetration of the instrument and are measured by varying the length of the tool and focusing the induced current.

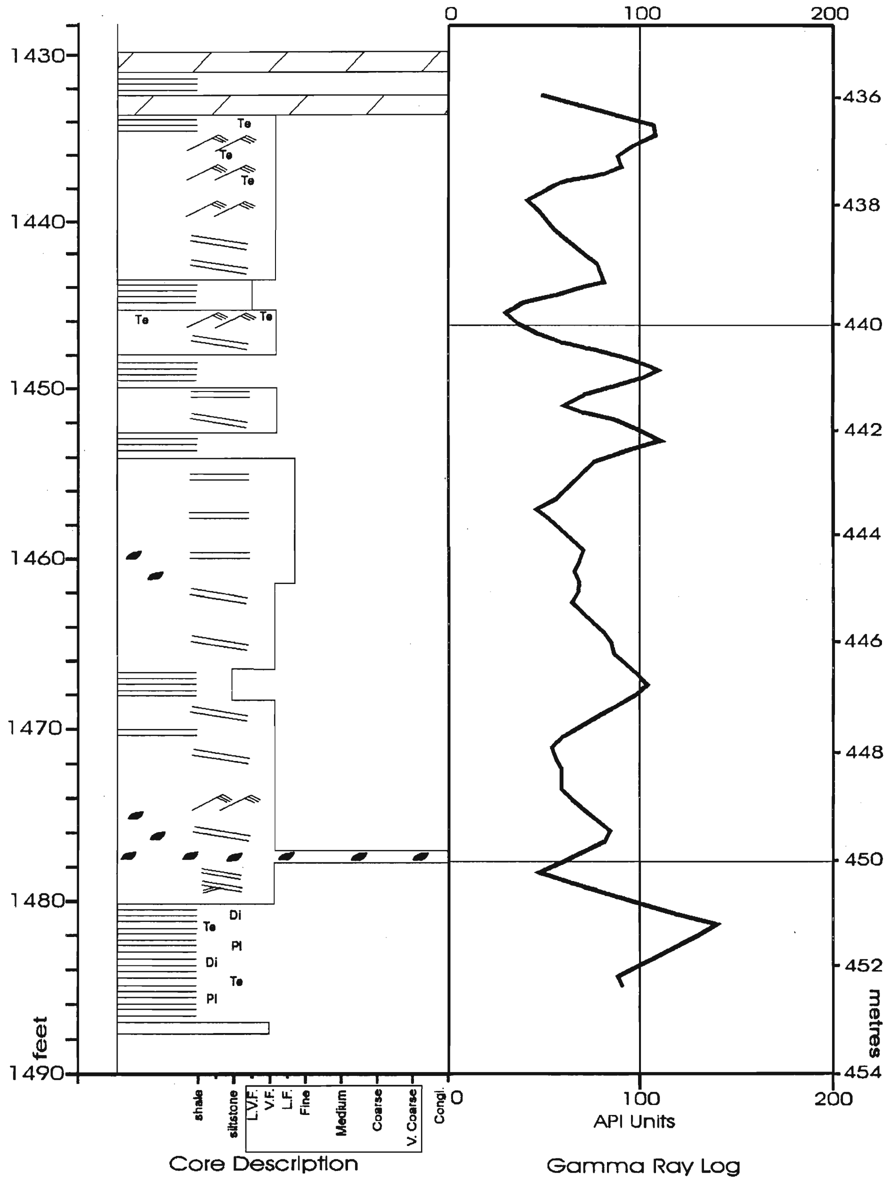
The compensated neutron-density series of curves is commonly displayed as estimates of porosity. The density tool emits gamma radiation which is scattered back to the detector in amounts proportional to the electron density of the rock which is related to the density of the rock, and the amount and density of pore fluids (Cant, 1992). In most cases, logs used in the study measured density porosity using a sandstone density of 2650 kg/m^3. The neutron log measures the concentration of hydrogen (in water or hydrocarbons) in the rock. The tool emits neutrons of a known energy level, then measures the energy of neutrons reflected from the rock. Resistivity logs and the neutron-lithodensity series of curves were available for a great majority of the drilled wells. Other well logs, such as the sonic log (the measure of the velocity of sound waves in rock), were

Well Name: Pembina #4 Lake Erie 91-S
Block Number: 91-S

Latitude: 42 31' 14.08" N
Longitude: 80 11' 16.52" W

Cored Interval: 1429 - 1488 ft.
435.5 - 453.4 m

K.B. Elev.: 593 ft. 180.7 m
Pet. Res. Core No.: #868



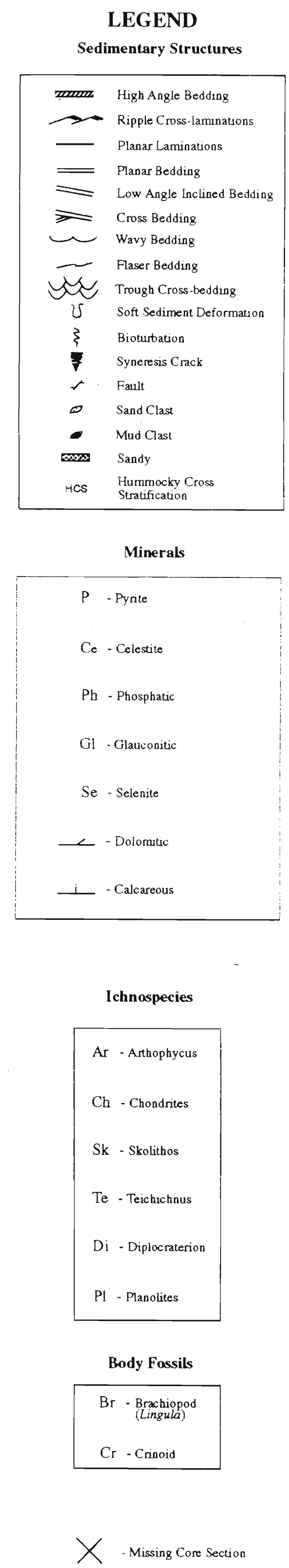


Figure 3: Core section, Pembina #4 Lake Erie, Block 91-S, illustrating the effectiveness of the gamma ray 100API units cutoff for determining 'clean' sand within the Grimsby and Thorold formations. This section has approximately 12.5m of sand which is confirmed by the gamma ray log. The legend is for all core sections in this study.

used to further enhance the database; these logs were less commonly available in the well files.

Older well files had forerunners of the above logs, such as a gamma ray curve with no API units scale. A very common older log was the neutron calibrator log, a forerunner of the neutron porosity curve. Instead of being a measure of the energy of neutrons reflected from the rock, the neutron calibrator device measures a direct count of neutrons, giving similar information as the neutron porosity curve.

Normally, the density porosity and neutron porosity curves are plotted together which aids in hydrocarbon detection by what is referred to as 'the gas effect crossover', a strong indicator of a natural - gas bearing zone. Liquid hydrocarbons have hydrogen indexes close to that of water. Gas, however, usually has a considerably lower hydrogen concentration that varies with temperature and pressure. Therefore, when gas is present within the tool's zone of investigation, a neutron porosity log reads too low a porosity and allows the neutron log to be used with other porosity logs to detect gas zones (the gas effect crossover) and identify gas/liquid contacts. However, the neutron calibrator log is not plotted with a density porosity curve on the same plot but does have the gamma ray log plotted beside it. The bulk density curve is on a separate plot.

The more common well log curves were digitized using the DigiRule system. These curves were: 1) gamma ray; 2) compensated neutron porosity; 3) density porosity; and 4) deep resistivity (Figure 4). If the compensated neutron porosity and density porosity were not available, the neutron calibrator and bulk density logs were digitized. Sonic logs, if run and included in the well file, were also digitized.

CORES

As of May, 1995, the Petroleum Resources Laboratory is a repository of 933 cores drilled in southern Ontario. Of this 933, 364 are from subsurface Lake Erie and approximately 275 include the Grimsby Formation. There are also several cores of the Cabot Head Formation which were logged for this study. The majority of the cores are eighteen metre sections but some are of much greater intervals and a few include the complete interval from the Queenston Formation through to the Rochester Shale.

Eighty-five cores were selected and described from bottom to top using a steel metric tape measure. Basic lithology and sedimentary structures were recorded. Grain size was determined using a standard grain size card obtained from CanStrat, Calgary, Alberta, by comparing core samples at intervals with this card under a binocular microscope. Trace fossils were identified and the intensity of bioturbation levels were noted and recorded using the semiquantitative classification scheme of Droser and Bottjer (1986). This classification scheme is based on a visual estimate of the intensity of disturbance of the original sedimentary fabric expressed on a scale of 1 through 6: 1) no bioturbation, 2) up to 10% of original bedding disturbed with discrete, individual burrows, 3) approximately 10 to 40% of original bedding disturbed with generally isolated burrows and some overlapping, 4) approximately 40 to 60% of original bedding disturbed with burrows overlapping and are not always well defined, 5) bedding is completely disturbed, but the burrows are still discrete in places and the fabric is not mixed, and 6) bedding is completely homogenized.

Core sections were drawn using a vertical scale of depth and a horizontal scale relative to grain size (Figure 5). The bioturbation intensity curve is shown horizontally

Well Name: Consumers 13226
Block Number: 155-A

Latitude: 42 24' 23.54" N
Longitude: 80 40' 05.63" W

Cored Interval: 1685 - 1751.5 ft.
513.6 - 533.9 m

K.B. Elev.: 619 ft. 188.7 m
Pet. Res. Core No.: #442

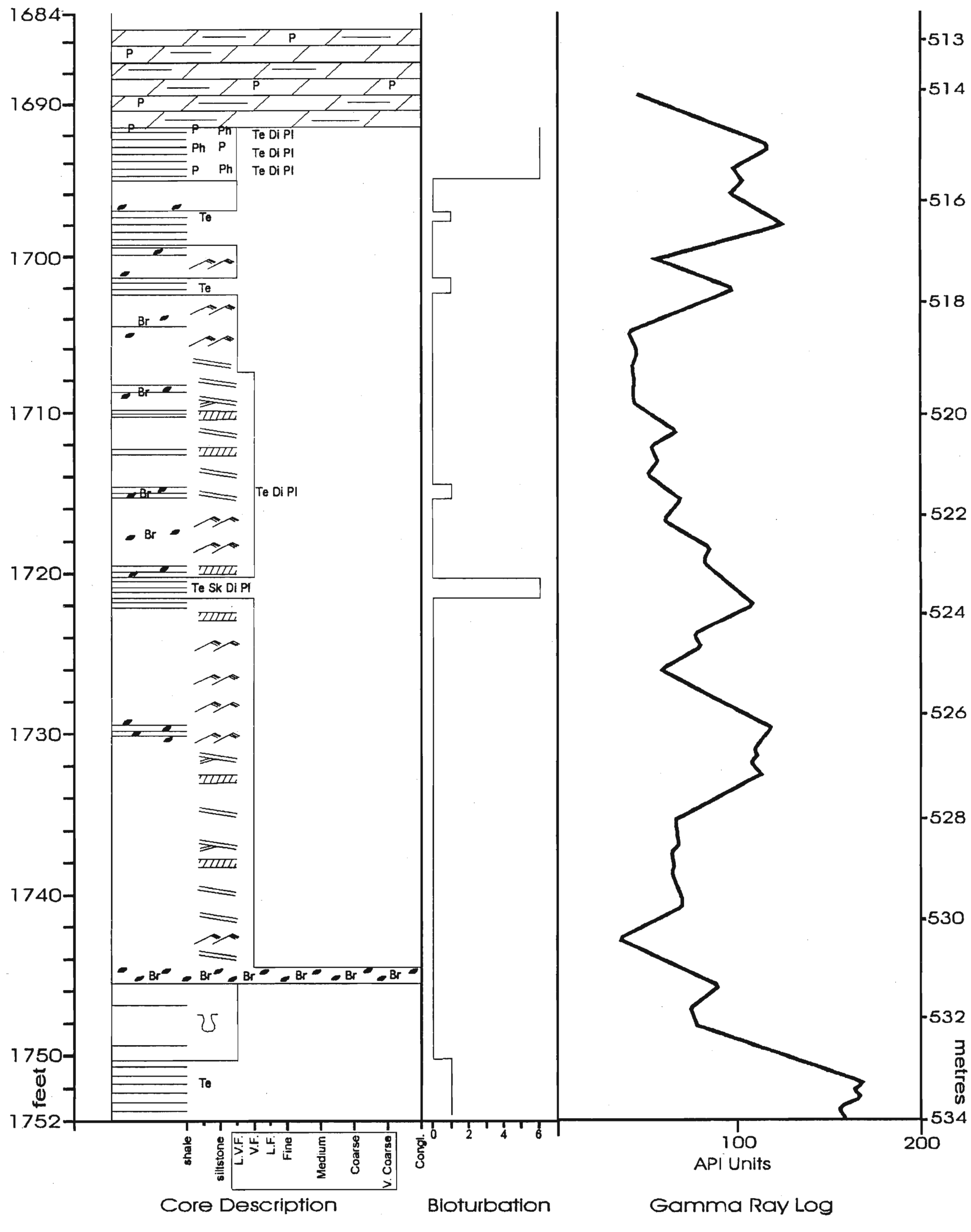


Figure 5: An example of a drawn core section (Consumers 13226 155-A) with bioturbation curve using Droser and Bottjer (1986) and gamma ray log curve over the cored interval.

adjacent to the drawn sections. The sedimentological sections based on core were then matched to their respective gamma ray curves which was plotted adjacent to the core sections and the bioturbation curve. The core sections were then compared to the geophysical well logs for the construction of cross-sections to aid and correct formation boundaries and facies interpretations.

CROSS SECTIONS AND DATABASE

Copies of the gamma ray logs were made over the interval from the Queenston Formation - Whirlpool (or Manitoulin) Formation unconformity to the datum point at the base of the Rochester Shale to construct cross-sections. The total number of well logs used in the making of the cross-sections was 1197. After constructing cross-sections, formation boundaries were established for the top of the Queenston Formation - base of Whirlpool (or Manitoulin) Formation, the top of the Cabot Head Formation - base of Grimsby Formation, the top of the Grimsby Formation - base of Thorold Formation, and the top of the Thorold Formation - base of Reynales Formation as well as the top of the Reynales-Irondequoit formations. These depths were entered into a database which included the well name, the well location, the file name of the digitized well log, and the K.B. (kelly bushing) elevation which is the elevation of the drilling floor above sea level (Figure 6).

The Queenston Formation - Whirlpool (or Manitoulin) Formation unconformity boundary was established as the lithological change from a shale to a sandstone in the case of the Whirlpool Formation, or to a carbonate, in the case of the Manitoulin Formation (Figure 7). The Cabot Head Formation - Grimsby Formation boundary was delineated on the basis of the shale deflection on the gamma ray geophysical well log (Figure 7). The log shifted sharply to the left (a decrease in API units) indicating an increase in grain size

Well Name	Block	File Name	L	X	K.B. Elev.		Queenston		Cabot Head		Grimsby		Thorold		Reynales		Net GR-TH		Core			T.D.	Status
					Ft.	M	Ft.	M	Ft.	M	Ft.	M	Ft.	M	Ft.	M	Sand		Y/N	Fm.	Interval	Formation	
																	(ft)	(m)					
Consumers 13285	125-W	con13285	B	F	616	187.8	1820	554.7	1727	526.4	1679	511.8	1675	510.5	1663	506.9	28	8.5	Y	GR	1672-1732'		GR-1679-1686'
Consumers 13652	125-Y	con13652	B	F	594	181.0	1795	547.0	1686	514.0	1654	504.0	1650	503.0	1637	499.0	30	9.0					D&A
Consumers 13825	126-A	con13825		F	595	181.2	1650	503.0	1568	478.0	1519	463.0	1508	459.5	1494	455.5	20	6.0					D&A
Telesis #4 13926	126-A	tel13926		F	595	181.2	1650	503.0	1558	475.0	1510	460.2	1508	459.7	1494	455.5	16	5.0	Y	GR	459-474.2m		D&A
Consumers 13278	126-E	con13278	B	F	618	188.4	1700	518.2	1609	490.4	1573	479.5	1561	475.8	1549	472.1	29	8.8	Y	GR	1558-1618'		D&A
Consumers 13168	126-F	con13168		F	619	188.7	1720	524.3	1637	499.0	1581	481.9	1575	480.1	1563	476.4	24	7.3	Y	GR	1578-1638'		GR-1579-1592'
Consumers 13312	126-G	con13312		F	620	189.0	1713	522.1	1620	493.8	1575	480.1	1569	478.2	1558	474.9	46	14.0	Y	GR	1568-1628'		GR-1592-95,1601-10'
Consumers 13447	126-I	con13447	B	F	617	188.1	1695	516.6	1602	488.3	1554	473.7	1551	472.7	1536	468.2	34	10.4					D&A
Consumers 13650	126-M	con13650	B	F	616	187.9	1718	523.5	1627	496.0	1582	482.2	1575	480.0	1563	476.3	10	3.0					D&A
Consumers 13556	126-N	con13556	B	F	616	187.6	1736	529.0	1645	501.5	1600	487.7	1595	486.0	1581	481.8	3	1.0					D&A
Consumers 13445	126-O	con13445		F	617	188.1	1753	534.3	1659	505.7	1611	491.0	1606	489.5	1593	485.5	44	13.4					GR-1612-1622'
Consumers 13836	126-Q	con13836		F	594	181.1	1762	537.0	1668	508.5	1621	494.0	1616	492.5	1603	488.5	20	6.0					D&A
Consumers 13837	126-S	con13837		F	595	181.2	1757	535.5	1663	507.0	1620	493.7	1612	491.2	1598	487.0	30	9.0					D&A
Anschutz #3	127-A	ans5461		F	594	181.1	1632	497.5	1536	468.0	1494	455.2	1485	452.5	1472	448.6	23	7.0					GR-455.3-460.2m
Anschutz #4	127-C	ans5462		F	594	180.9	1635	498.3	1545	471.0	1494	455.5	1490	454.0	1476	450.0	16	5.0					GR-456-466m
Consumers 13902	127-E	con13902		F	595	181.2			1551	472.8	1503	458.0	1497	456.4	1486	452.8	30	9.0				Cabot Head	GR-459.5-472.5m
Pembina #3	127-H	pem5633		F	593	180.8	1678	511.5	1584	482.8	1536	468.2	1531	466.7	1519	463.0	43	13.0					GR-468.5-471.0m
Anschutz #4	127-M	ans5493		F	594	181.1	1703	519.0	1614	491.8	1562	476.0	1557	474.5	1544	470.5	7	2.0					D&A
Pembina #1	127-O	pem5634		F	593	180.6	1683	513.0	1581	482.0	1545	471.0	1538	468.8	1526	465.0	18	5.5					D&A
Anschutz #4	128-F	ans5432		F	592	180.3	1672	509.5	1576	480.3	1527	465.4	1521	463.5	1507	459.3	52	16.0					D&A
Anschutz #4	128-Q	ans5473		F	592	180.5	1766	538.2	1669	508.8	1614	492.0	1610	490.8	1596	486.5	75	23.0					D&A
Anschutz #4	129-I	ans5434		F	592	180.5	1666	507.7	1581	482.0	1519	463.0	1516	462.0	1503	458.0	56	17.0					D&A
Pembina #1	129-Q	pem5620		F	593	180.7	1738	529.7	1633	497.8	1591	485.0	1586	483.4	1572	479.1	33	10.0					D&A
Anschutz #4	129-R	ans5444		F	591	180.1	1770	539.5	1680	512.0	1621	494.0	1618	493.2	1604	489.0	39	12.0					D&A
Anschutz #4	130-C	ans5452		F	592	180.4	169[illegible]	516.0	1614	492.0	1549	472.0	1544	470.5	1529	466.0	61	18.5					D&A
Anschutz #4	130-F	ans5425		F	594	181.0	1676	510.8	1588	484.0	1532	467.0	1529	466.0	1515	461.8	46	14.0					GR-474.4-476.2m
Anschutz #4	130-K	ans5453		F	592	180.4	1726	526.0	1645	501.3	1581	482.0	1576	480.4	1562	476.0	66	20.0					D&A
Anschutz #4	130-M	ans5454		F	591	180.1	1723	525.0	1623	494.8	1575	480.0	1570	478.6	1555	474.0	41	12.5					GR-484.7-505.8m
Pembina #3	130-Q	pem5621		F	594	180.9	1760	536.5	1686	514.0	1627	496.0	1623	494.8	1608	490.2	48	14.5					D&A
Consumers 13839	150-F	con13839		F	594	181.1	1855	565.5	1762	537.0	1713	522.0	1706	520.0	1693	516.0	20	6.0					GR-?
Consumers 13736	151-D	con13736	B	F	594	181.1			1749	533.0	1696	516.8	1689	514.8	1677	511.0	25	7.5				Cabot Head	D&A
Consumers 13653	151-G	con13653	B	F	594	181.0	1844	562.0	1752	534.0	1697	517.3	1692	515.8	1680	512.0	23	7.0					D&A
Consumers 13838	151-I	con13838		F	595	181.3	1865	568.5	1770	539.5	1721	524.5	1713	522.2	1700	518.0	28	8.5					D&A
Consumers 13841	151-P	con13841		F	594	181.1			1850	564.0	1791	546.0	1787	544.5	1773	540.5	26	8.0					D&A
Consumers 13185	152-B	con13185		F	617	188.1	1846	562.7	1752	534.0	1710	521.2	1700	518.2	1687	514.2	34	10.4	Y	GR	1698-1755'		GR-1722-1726'
Consumers 13332	152-C	con13332	B	F	617	188.1	1862	567.5	1767	538.6	1720	524.3	1715	522.7	1702	518.8	20	6.1					D&A
Consumers 13557	152-D	con13557		F	617	188.0	1837	560.0	1742	531.0	1695	516.5	1689	514.8	1676	510.7	38	11.5					GR-517-523.7m
Consumers 13654	152-E	con13654	B	F	595	181.3	1890	576.0	1793	546.5	1749	533.0	1741	530.5	1726	526.0	20	6.0					D&A
Consumers 13655	152-E	con13655		F	595	181.2	1839	560.5	1742	531.0	1695	516.5	1690	515.0	1677	511.0	39	12.0					GR-517-521.5m
Consumers 13787	152-E	con13787		F	594	181.1	1809	551.5	1713	522.0	1667	508.0	1662	506.5	1649	502.5	41	12.5					D&A
Consumers 13167	152-N	con13167	B	F	617	188.1	1931	588.6	1839	560.5	1784	543.8	1778	541.9	1764	537.7	23	7.0	Y	GR	1775-1834'		D&A
Consumers 13101	152-Y	con13101	B	F	615	187.5	1980	603.5	1876	571.8	1835	559.3	1826	556.6	1812	552.3	40	12.2	Y	GR	1825-1877'		D&A

Figure 6: Portion of database compiled with data collected from cross-sections constructed from geophysical well logs indicating well name, location, K.B. elevation, and various formation boundaries. 'L' is whether Brock files have a hard copy of the well logs and 'X' is the cross section file, in this case 'F'. Also included is the "Net GR-TH Sand' which is the thickness of sand in the Grimsby and Thorold formations based on a gamma ray reading of 100 API units, whether the hole has a core available, what formation was cored and the interval. The last formation penetrated (T.D. Formation) is also listed as well as the final status of the well. This last column was compiled using Ministry of Natural Resources files which contained some ambiguous information e.g. drill stem test intervals possibly recorded as production intervals.

from predominantly shale and rare thin bedded, very fine grained sands to the much thicker bedded, coarser grained sandstone of the Grimsby Formation. These sandstone beds are centimetres thick in the Cabot Head Formation and abruptly become metres thick in the lower portions of the Grimsby Formation. In addition, the neutron porosity curve generally shifts to the right indicating a change in lithology from primarily shale to sandstone and the density porosity shifts to the left indicating a general decrease in the density of the rock and the presence of pore space, possibly occupied by natural gas. In many cases, a 'gas effect crossover' was present, beginning at the base of the Grimsby Formation and continuing upwards in the section for several metres.

The boundary between the Grimsby Formation and the Thorold Formation was more problematic. Commonly, but not always, the two formations are very similar in their appearance on wireline well logs (Figure 7). In cores, the Thorold Formation is generally more highly bioturbated and is lithologically a very fine grained sandstone interbedded with shale. The boundary was therefore chosen at the point of deflection to the right on the gamma ray log indicating a change from a slightly coarser grained sandstone to a finer grained sandstone. This change in grain size was verified in subsurface by cores and coincided with the increase of bioturbation, where bioturbation was present.

The boundary between the Thorold Formation and the Reynales Formation was chosen as the point of sharp gamma ray deflection to the left indicating a change in lithology from a shale-sandstone to a dolomite (Figure 7) as well as a shift to the right on the neutron - density log. The datum point for many sections was chosen as a sharp deflection to the right on the gamma ray well log indicating a lithological change from the dolomite of the Irondequoit/Reynales Formations to the mixed carbonate-shales of the Rochester Formation. The contact between the Irondequoit/Reynales and the Rochester formations was used as the datum for cross-sections, the database and maps.

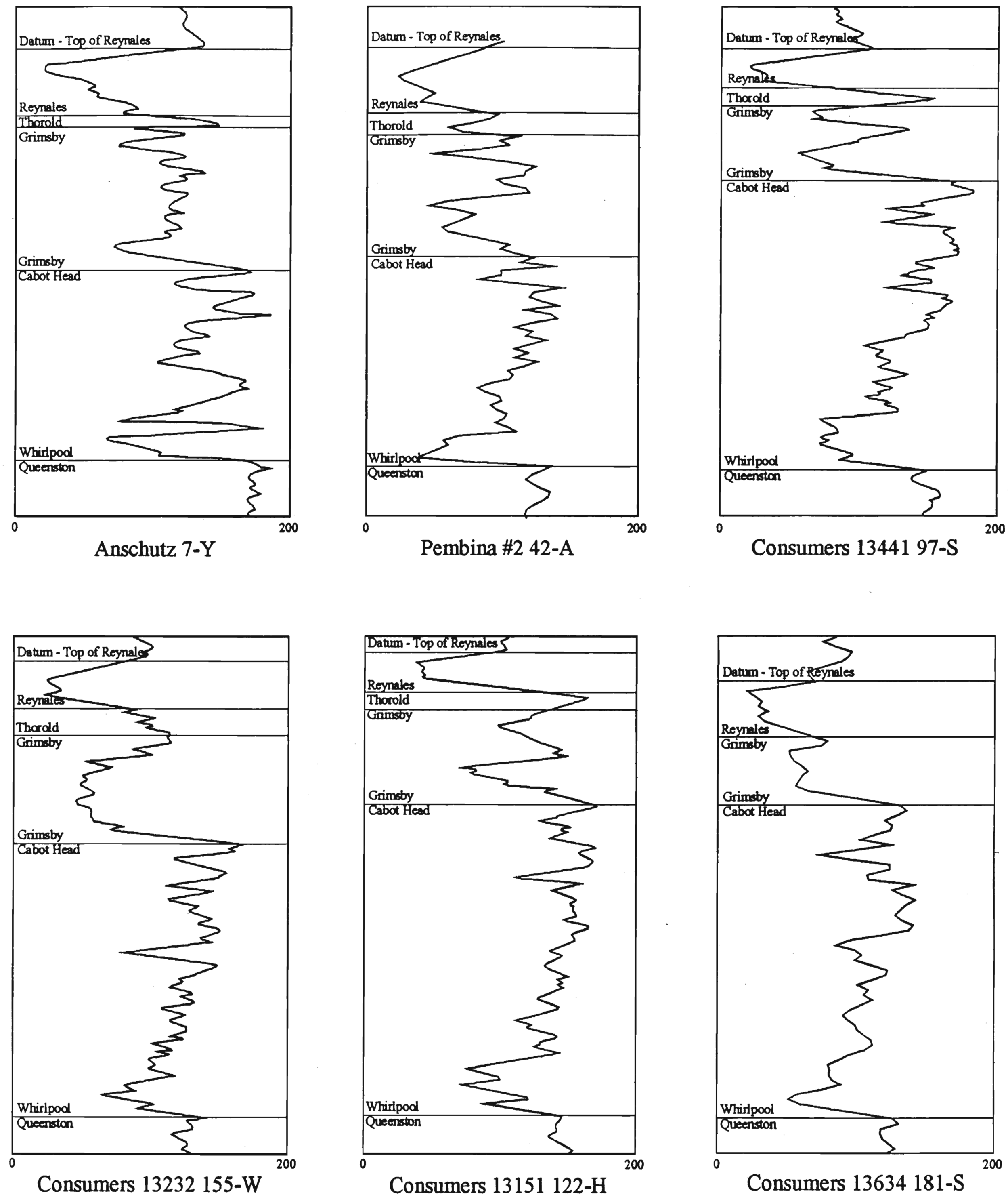


Figure 7: Representative formation boundary picks from wells in several areas on Lake Erie using gamma ray logs. Where picks were ambiguous and problematic, core sections were utilized along with other well log curves. The top of the Whirlpool Formation was not picked as it was outside the parameters of this thesis. No vertical scale is implied.

After creating a database of formation tops and constructing cross-sections, several secondary sand bodies within the Cabot Head Formation were noted and a database compiled in which their depths and thicknesses were recorded.

MAPS

After the compilation of the data from geophysical well logs, cross-sections, and core analyses, a series of structural contour maps of formation boundaries and total sand content were created. Four regional maps were constructed: 1) Total Queenston - Reynales/Irondequoit Isopach, a map indicating the thickness of the Cataract Group along with the Reynales/Irondequoit formations, 2) Total Grimsby - Thorold Isopach, a map delineating the subcrop boundaries of the Grimsby and Thorold formations and the thickness of the formations and, 3) Total Grimsby - Thorold Sand Isopach, a map indicating the thickness of the sands of the Grimsby and Thorold formations based on a gamma ray log value of 100 API units to determine any trends for the sands.

PALYNOLOGY

As well as determining the lithologies, bioturbation levels, and the identification of body and trace fossils of the measured core sections, eight shale samples were obtained for palynological analyses. Each sample was crushed to coarse sand size fragments and placed in a 10 percent solution of HCl for 24 hours in order to remove as much of the carbonates as possible from the sample. The solution was decanted off and the remaining residue was washed three times in distilled water. The residue was then placed in a 25 percent solution of HF at room temperature for 10 to 14 days to remove the silicates from the sample. The resulting residue was centrifuged and washed three times in distilled water. The sample was then placed in a 10 percent solution of HCl in a water bath which was brought to a boil. This removed any calcium flouride from the sample. After 30 minutes the solution was centrifuged and the residue washed three times in distilled water. A small drop of residue was mounted on a glass slide in corn syrup with three slides being made for each sample. Each slide was examined at 100x and 200x under a light transmitting microscope and any palynomorphs that were present were identified.

PROBLEMS ENCOUNTERED DURING DATA COLLECTION

During the process of data collection, many problems were encountered. Many wells were not drilled to a depth which allowed for the geophysical well logging tools to 'see' formation boundaries. Therefore, the Queenston Formation - Whirlpool boundary, the lowest boundary in the interval was missing from the data set for mapping purposes (Figure 8). Also, as previously mentioned, older geophysical well logs were quite common (Figure 9) and had to be reconciled with, newer, more sophisticated logs. Presentation of many older geophysical well logs was also unusual (Figure 10a), some only available in a small scale (1:600; Figure 10b) rather than the more common and accepted expanded scale of 1:240. Further, older wells were drilled using imperial measurements which had to be converrted to the metric scale. Scales for geophysical well logs whether in metric or footage are the same.

The identification of actual well locations was also a problem in many instances. Wells drilled before the mid-eighties by several operators did not include a location with a quarter tract identified. There were many tracts within a block where multiple wells were drilled without identifying which quarter the well was located in. All wells had to be reconciled using latitudes and longitudes which slowed the map making process

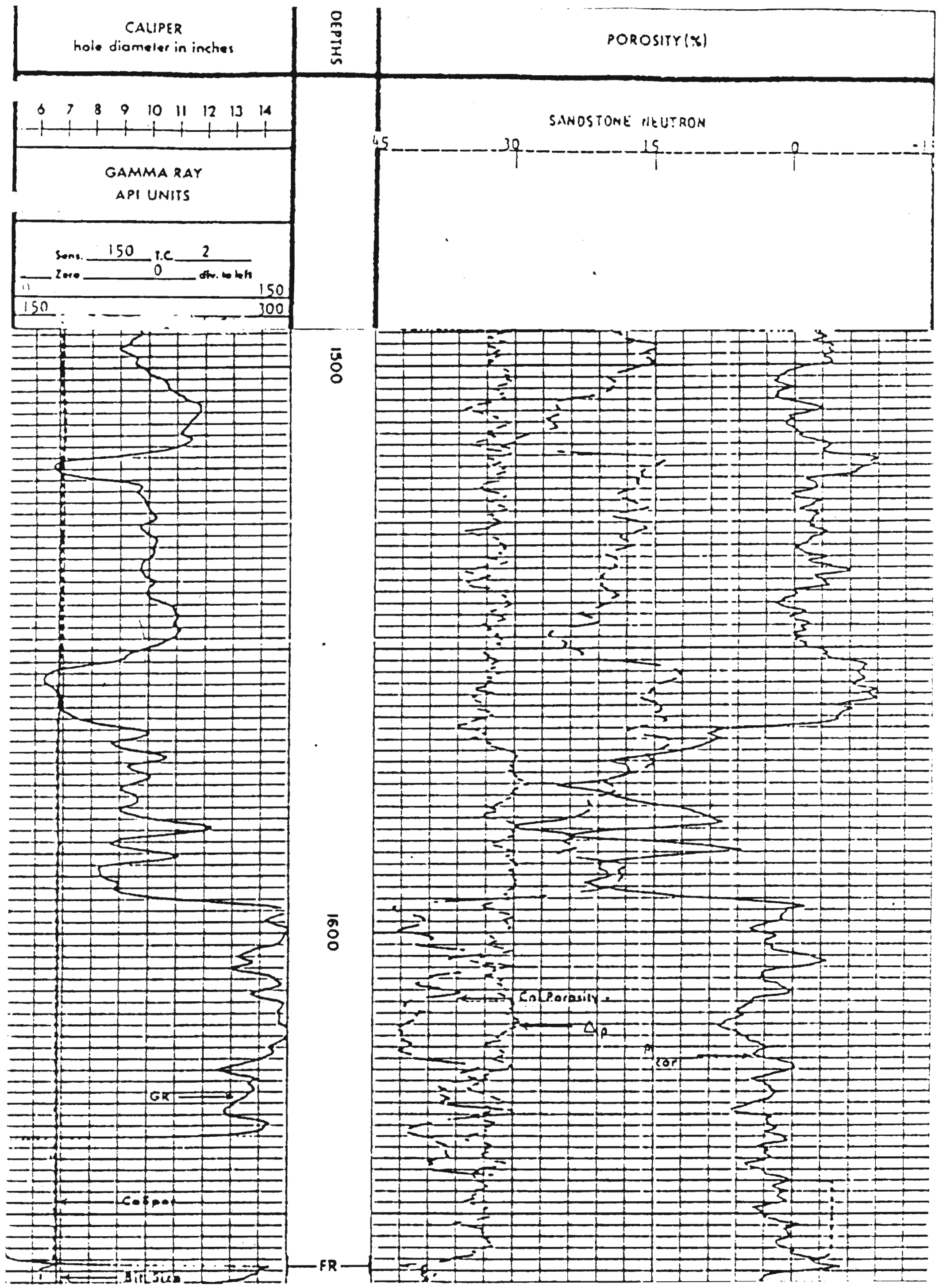


Figure 8: Well log traces (Consumers 13323, Block 97-Y) which do not include Queenston - Whirlpool formation boundary. In this case, the well reached total depth in the Cabot Head Formation. This was common, especially with Consumers Gas as the operator but occurred with other operators as well. Other wells reached total depth within the Queenston Formation but the well logs could not pick up the formation boundary. Because of tool length and instrument locations, the gamma ray log needs nine metres of bottom hole to begin readings.

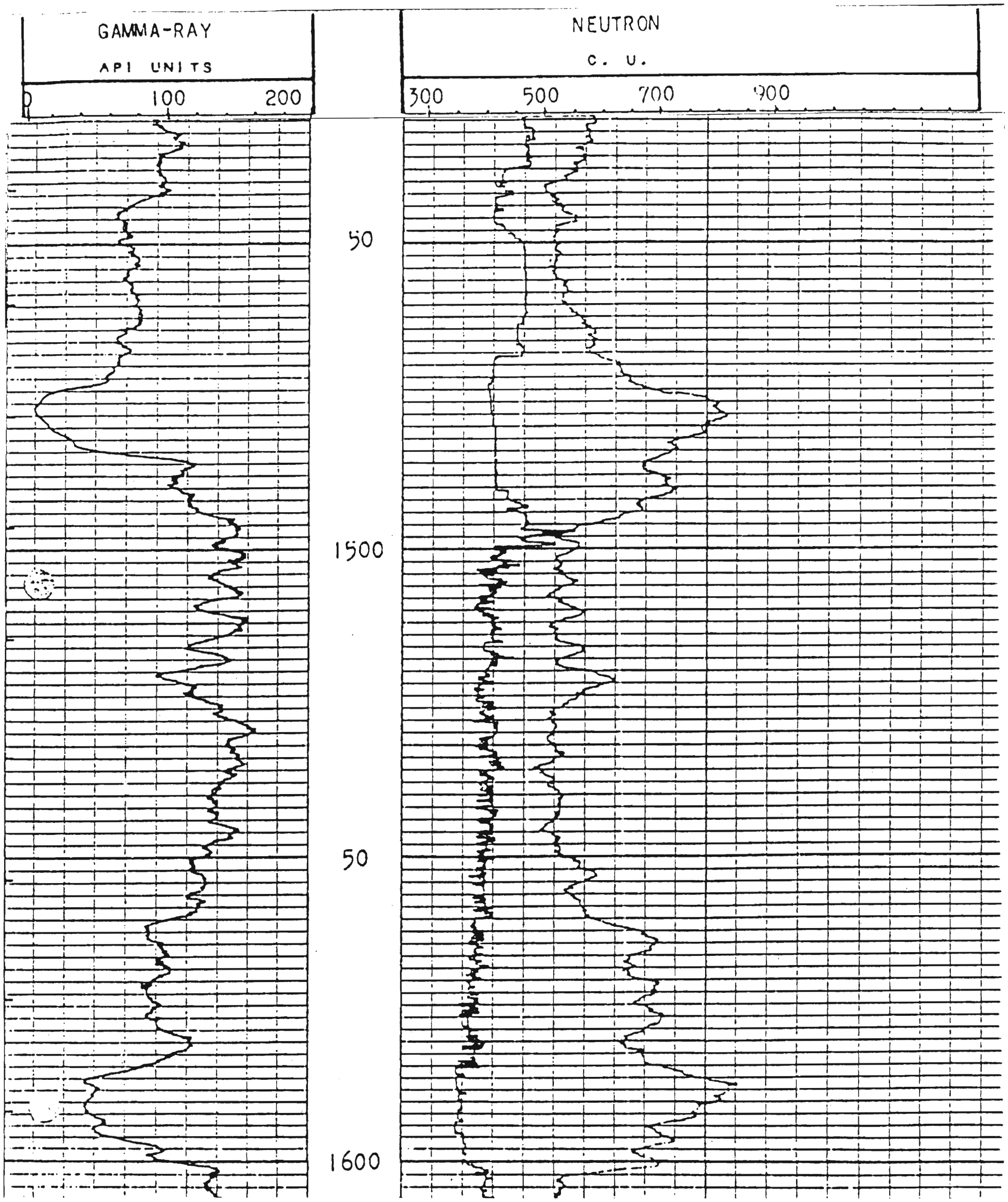


Figure 9: A neutron calibrator log (right curve). Scale is actual counts from one detector rather than a ratio from two with actual estimated porosity which the modern neutron porosity curve displays. The gamma ray curve (left) is in API units. Older well logs than this one would have the gamma ray curve scale labelled as radiation increasing to the right with no given scale.

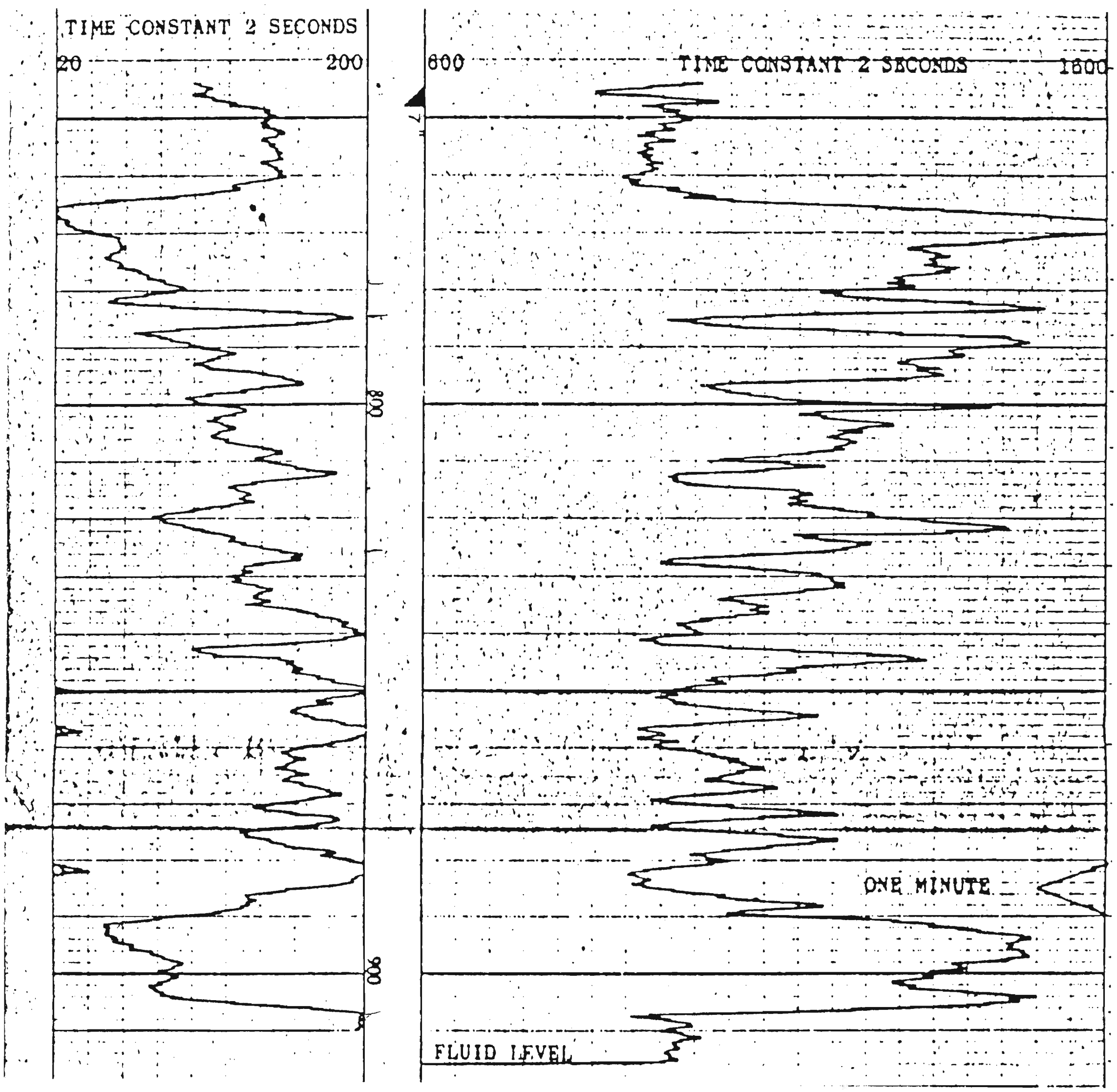


Figure 10a: Well log (gamma ray - neutron calibrator) from well drilled in 1961 (Long Point Port Dover 23-14, Block 8-X) illustrating a very unusual presentation. Note the scale for the neutron calibrator (right). Lithologic interpretation of the log was problematic.

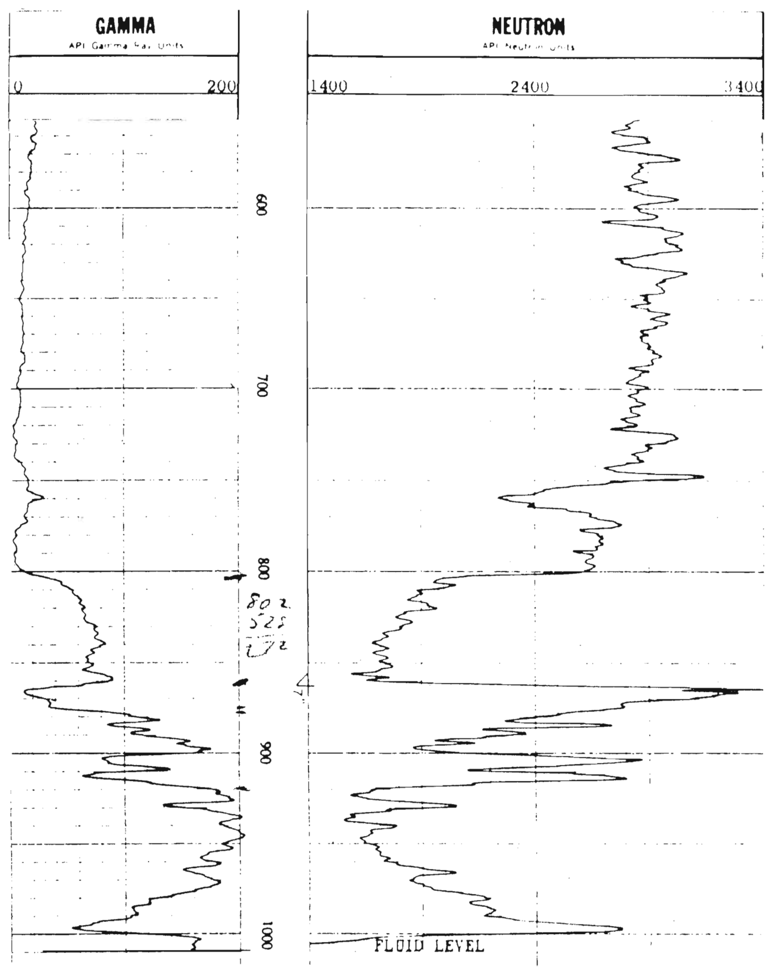


Figure 10b: Well log (gamma ray - neutron calibrator) from well drilled in 1962 (Place Walpole 28, Block 16-S) illustrating a 1:600 scale presentation, the only one available. With this scale, only an approximate boundary pick can be ascertained. Note the scale for the neutron calibrator log which is considerably different from that found in Figure 10a and Figure 9.

considerably until wells were properly located.

Over the course of this study, it was concluded that the formation picks contained on the various forms within the files at the Petroleum Resources Laboratory were inconsistent. Numerous geologists from the Ministry of Natural Resources and well operators identified the formation boundaries from many different geological and geophysical parameters. This caused common inconsistencies to appear in the data supplied by the files, the most problematic being the inconsistent pick for the boundary of the top of the Cabot Head Formation and the base of the Grimsby Formation. In forming the database for this study, it was decided to ignore the previous formation boundary picks to allow a consistent data set based on a single set of geological and geophysical parameters common to all the geophysical well logs, core sections and well file data.

REGIONAL GEOLOGICAL SETTING

REGIONAL GEOLOGIC HISTORY

The Silurian Cataract Group of Ontario, which includes the Grimsby Formation and its correlatives of the Medina Group in New York State and Pennsylvania, were deposited in the northern end of the Appalachian Foreland Basin (Brett *et al.*, 1990). Along its southeastern margin, the basin was bordered by a linear belt of uplifted Middle to Upper Ordovician shales and sandstones and, farther to the east, by the Taconic orogenic belt from which Silurian siliciclastic sediments were derived. The Appalachian Basin was bordered along its northwestern margin by the northern extension of the Findlay Arch, which is actually a series of closely spaced uplifts, and the Algonquin Arch (Figure 11). Table 3 summarizes the stratigraphic nomenclature for eastern North America from Virginia, Pennsylvania, central and western New York, southern Ontario, Ohio, and Michigan during the Ordovician and Silurian.

During the Late Precambrian, rifting of the Grenville basement formed an Atlantic-type continental margin along the eastern boundary of North America (Quinlan and Beaumont, 1984). This margin stabilized as a major carbonate bank by the Early Ordovician (Rodgers, 1968; Thomas, 1977). The Appalachian Foreland Basin developed from the compression of this passive, carbonate-dominated, continental margin during collision with an island arc system during the Middle Ordovician (Brett *et al.*, 1990). The first evidence of the approach of allochthonous terranes and the Taconic Orogeny is the rapid depression of the carbonate bank during the Early to Middle Ordovician followed by the influx of black shales, turbidites, and the sequentially more proximal molasse of the Sevier Basin centred on eastern Tennessee (Shanmugam and Walker, 1978, 1980; Quinlan and Beaumont, 1984). Carbonate bank depression was preceded by widespread uplift and

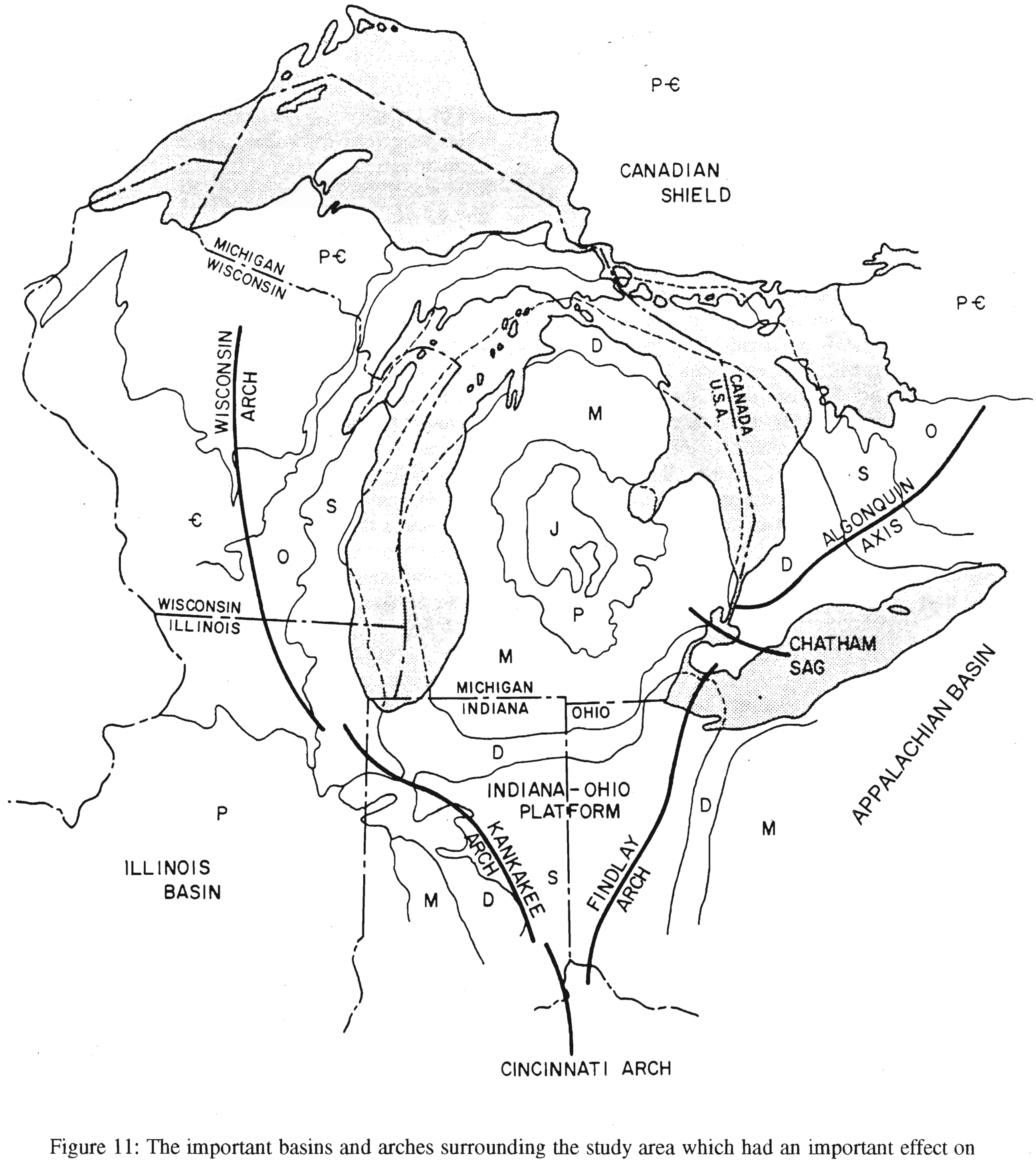


Figure 11: The important basins and arches surrounding the study area which had an important effect on the geology within the region (after Reszka, 1991).

erosion of the Beekmantown, Knox, and correlative formations, resulting in an unconformity.

In many parts of the Appalachian Basin, there is evidence of a Late Ordovician to Early Silurian tectonic rejuvenation of the Taconic Front (Quinlan and Beaumont, 1984; Beaumont *et al.*, 1988). From the Late Middle Ordovician until the end of the Ordovician, there was a second stage of downwarping centred on Pennsylvania and New York. This downwarping was accompanied by the deposition of a second package of clastic sediment, very similar to that of the Sevier Basin, recorded by the Bald Eagle - Oswego sandstone wedge and culminating in the formation of the Juniata - Queenston red bed succession (Zerrahn, 1979; Brett *et al.*, 1990). Virginia and West Virginia, positioned between the two clastic wedges, received carbonate deposition along the northwest flank of the Sevier Basin during the Middle Ordovician (Colton, 1970; Read, 1980). Following Late Ordovician downwarping, the northern foredeep extended southward and the Martinsburg Formation and equivalents were deposited.

The two foreland depocentres preserve the record of the Taconic Orogeny on the craton. Quinlan and Beaumont (1984) suggested from the timing of deposition and the shapes of the depocentres that the Taconic Orogeny was not simultaneous along the orogen, nor were the magnitudes and distribution of downwarping uniform. Although less intense, downwarping and clastic sedimentation continued in the Appalachian Basin until the end of the Clinton Stage, including the time of deposition of the Cataract Group in Ontario. This suggests that the Taconic Orogeny did not end with the Ordovician but rather in the Silurian. In New York State, evidence for a late Taconic pulse lies in the regionally extensive, low-angle unconformity at the Ordovician - Silurian boundary and an overlying thick Early Silurian clastic wedge that includes the Whirlpool Sandstone, Cabot

Stratigraphic Nomenclature

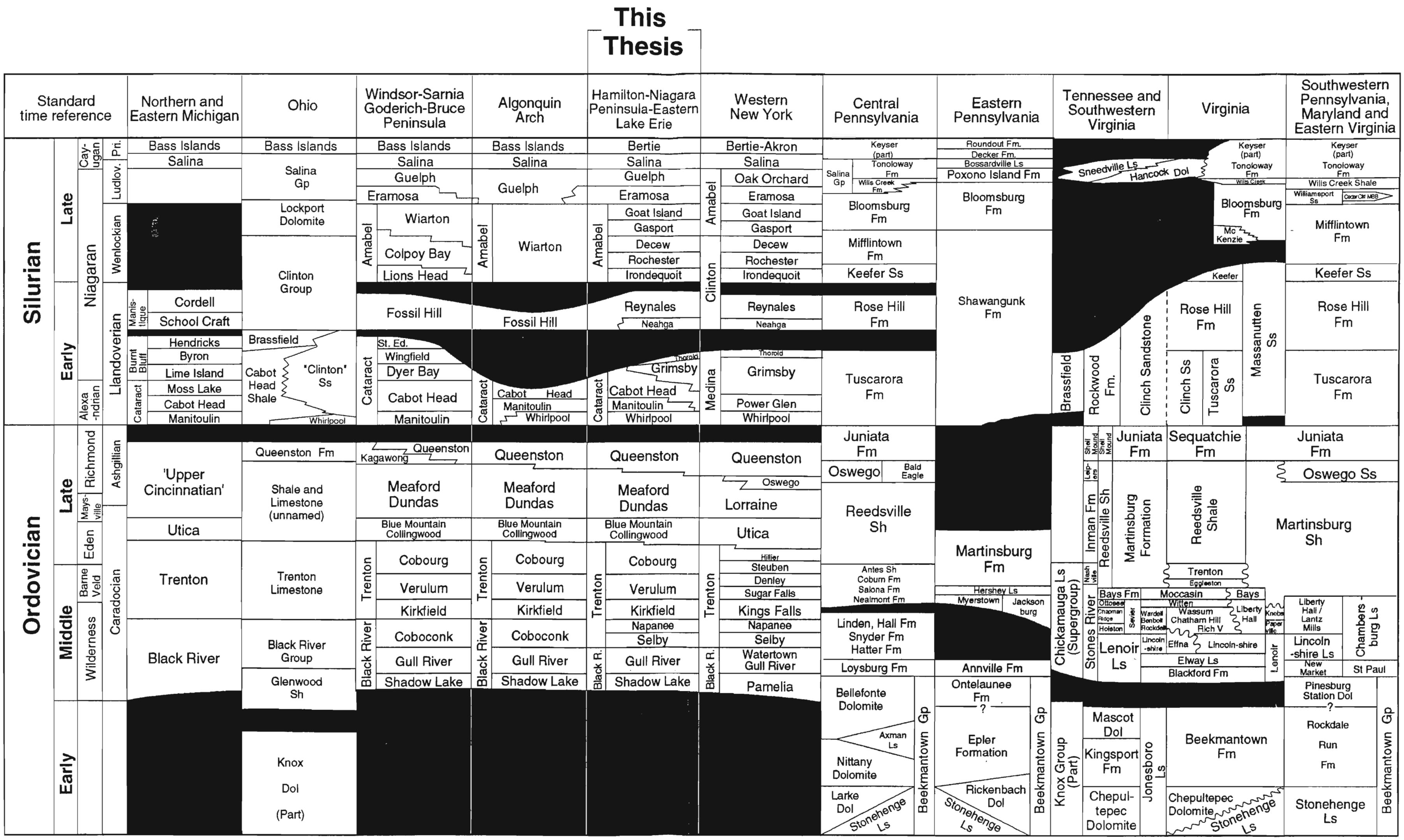


Table 3: Stratigraphic nomenclature for Virginia, Maryland, Pennsylvania, central and western New York, the Niagara Peninsula and eastern Lake Erie, southwestern Ontario, Ohio, and Michigan (compiled from Winder and Sanford, 1972; Millici and Witt, 1988).

Head and Grimsby formations (Brett *et al.*, 1990). Late tectonic events are also suggested by tilting to the northeast during the middle Ordovician to the period of Whirlpool Sandstone deposition in the Early Silurian (Rutka *et al.*, 1991). Medial Silurian strata of the Clinton Group become finer-grained, indicating a period of quiescence.

Quinlan and Beaumont (1984) further stated that sedimentation within the interior regions of the continent to the west of the present limit of the Appalachian Basin suggests considerable differences between the Early to Middle Ordovician and Late Ordovician. In their model, they suggested that there was not only deposition but also erosion on the arches and domes, both immediately after deposition and during subsequent periods of uplift. Their evidence for submergence and uplift of the arches and domes along with lithostratigraphic reconstructions (King, 1977; Borella and Osborne, 1978) demonstrates that the Sevier Basin extended sufficiently far west that it tilted the Illinois Basin. Similarly, Quinlan and Beaumont, (1984) also suggested that during the Late Ordovician the Michigan Basin's circular platform was almost totally destroyed by tilting towards the east as it and the adjacent Findlay Arch became part of the Appalachian Basin (Cook and Bally, 1975). This had a profound effect on the deposits of the study area. However, although there is very little evidence for actual emergence, the Algonquin Arch greatly reduced the rates of subsidence to the north of the study area and formed an effective barrier to the northwestward spread of terrigenous sediments of Taconic origin. The Findlay Arch was less effective as clastic sediments from the Taconic orogeny crossed the arch and were deposited to the west.

During the Late Ordovician - Early Silurian, paleomagnetic evidence suggests that North America moved only very slowly in latitude (Van der Voo, 1988; Ziegler *et al.*, 1977; Ziegler *et al.*, 1979). The study area was situated in the southern hemisphere at approximately 30 degrees south latitude, and North America was rotated about 45 degrees clockwise from its present position. Geological evidence indicates that the climate was probably warm and seasonally arid as abundant mud-cracks and traces of gypsum are found in the Queenston Formation (Middleton, 1987). The warm climate persisted through much of the Silurian with the development of reefs in the Lower and Middle Silurian; the region was arid at this time as suggested by the widespread development of evaporites in the Michigan and Appalachian Basins by the Late Silurian. The increased occurrence of evaporites could also be partly attributed to a fall in sea level with a consequent restriction of water circulation within the Appalachian Basin (Middleton, 1987).

During the Late Ordovician, a period of continental glaciation centred in Africa has been suggested by many authors (Beuf *et al.*, 1966; Fairbridge, 1971; Berry and Boucot, 1973; McClure, 1978). It has been recorded at many locations as geographically separate as Morocco, Mauritania, Mali, Chad, northern Ethiopia, Saudi Arabia and South Africa. It has also been recorded in Europe in southern Spain, and in South America in Argentina, Peru, and Bolivia (Figure 12). The age of this event is best documented in Morocco and is dated with a glacial maximum in late Ashgillian (Dennison, 1976) which approximately coincides with the time of the deposition of the Queenston Formation. It has been suggested that pulses of glaciation continued for some time into the early Silurian before ending entirely (Johnson *et al.*, 1985). McElhinny and Briden (1971) postulated that the Ordovician pole was in north-west Africa, shifting position to South Africa from Late Ordovician to Late Silurian. In the Early Silurian, the study area was situated relatively close to the paleo-equator in the southern hemisphere from 15 to 25 degrees south latitude (Ziegler *et al.*, 1977).

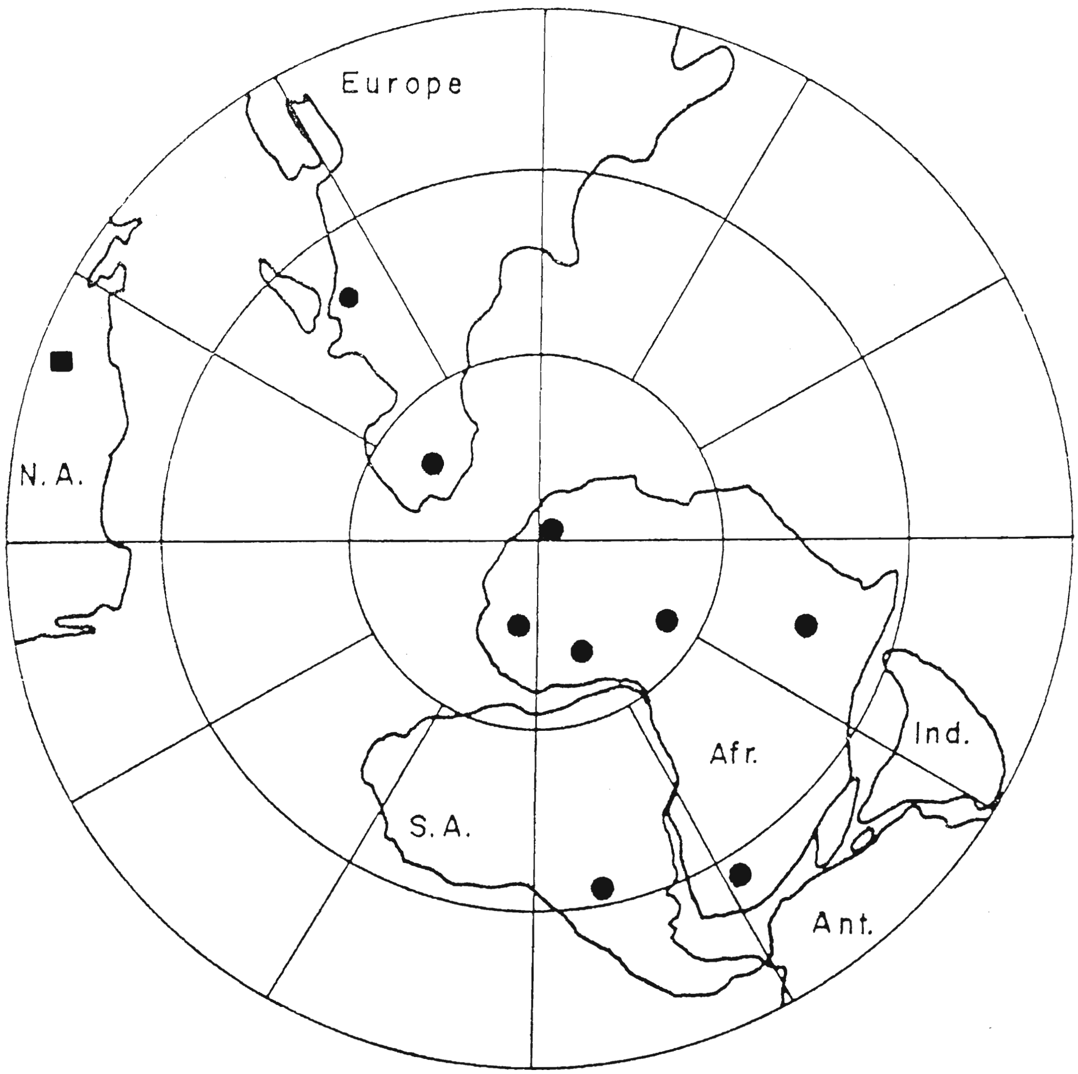


Figure 12: Location of study area in relation to reported locations of Late Ordovician - Early Silurian glaciation. Solid circles are reported locations of glaciation, square is location of study area (after Dennison, 1976).

CYCLICITY IN THE APPALACHIAN FORELAND BASIN

Johnson *et al.* (1985) used benthic assemblages to identify sea level changes on the North American Early Silurian platform and compared these sea level curves to those from the Early Silurian Yangtze Platform of China. This comparison suggested a series of transgressive-regressive cycles in the Early Silurian which can be traced from continent to continent and may be attributed to the eustatic sea-level changes due to the combined effects of the lingering glaciation in Gondwana (Africa and surrounding continents; Figure 12) and the rapid rate of sea-floor spreading which dispersed the cratons through middle Paleozoic oceans. After the initial melting of the Late Ordovician - Early Silurian glaciers in Africa, four smaller cycles of sea-level fluctuation were recorded by recurrent, shelly, benthic assemblages in a predominantly carbonate setting on the North American platform. Peaks in sea-level occurred in late Rhuddanian or early Idwian, early Fronian, early Telychian and late Telychian times (Johnson *et al.*, 1985; Figure 13). Although absolute age control is poor, the periodicity of these events may have been every two and half million years. Three of these peaks are identifiable on the Yangtze Platform of central and southwestern China.

The Late Ordovician - Early Silurian rise in sea level and the cycles recognized by Johnson *et al.* (1985) are examples of glacial eustacy where sea level change is associated with the melting and forming of glaciers. The cycles correspond to the third order cycles of Vail and a host of co-workers (Payton, 1977; Figure 14) identifying three orders of sequences that may be traceable over major areas of oceans as well as continents. Pitman (1978) suggested two categories of sea level change, one being where the actual volumes of sea water changed, and the second being where the size of the basins holding the water has changed. With continental glaciation occurring in Africa, the total volume of sea water has decreased. As the glaciers melted, sea water volumes increased and sea level subsequently rose.

Further work (Miall, 1990) has identified five orders of cycles within the geologic record with first order cycles lasting 400-500 million years and fourth and fifth order cycles less than 500,000. Third order cycles have a duration of 1 to 10 million years. Bennacef *et al.* (1971) identified a series of strata in Algeria associated with the Late Ordovician - Early Silurian glaciation in Africa which was subsequently attributed to third order cycles.

Because of a relatively gentle paleo slope, glacioeustatic sea level changes could have a large affect on the study area. A transgression followed by minor drops in sea level would have allowed large areas of deeper marine deposits to have been subjected to higher energy, nearshore environments where erosional processes could have taken place.

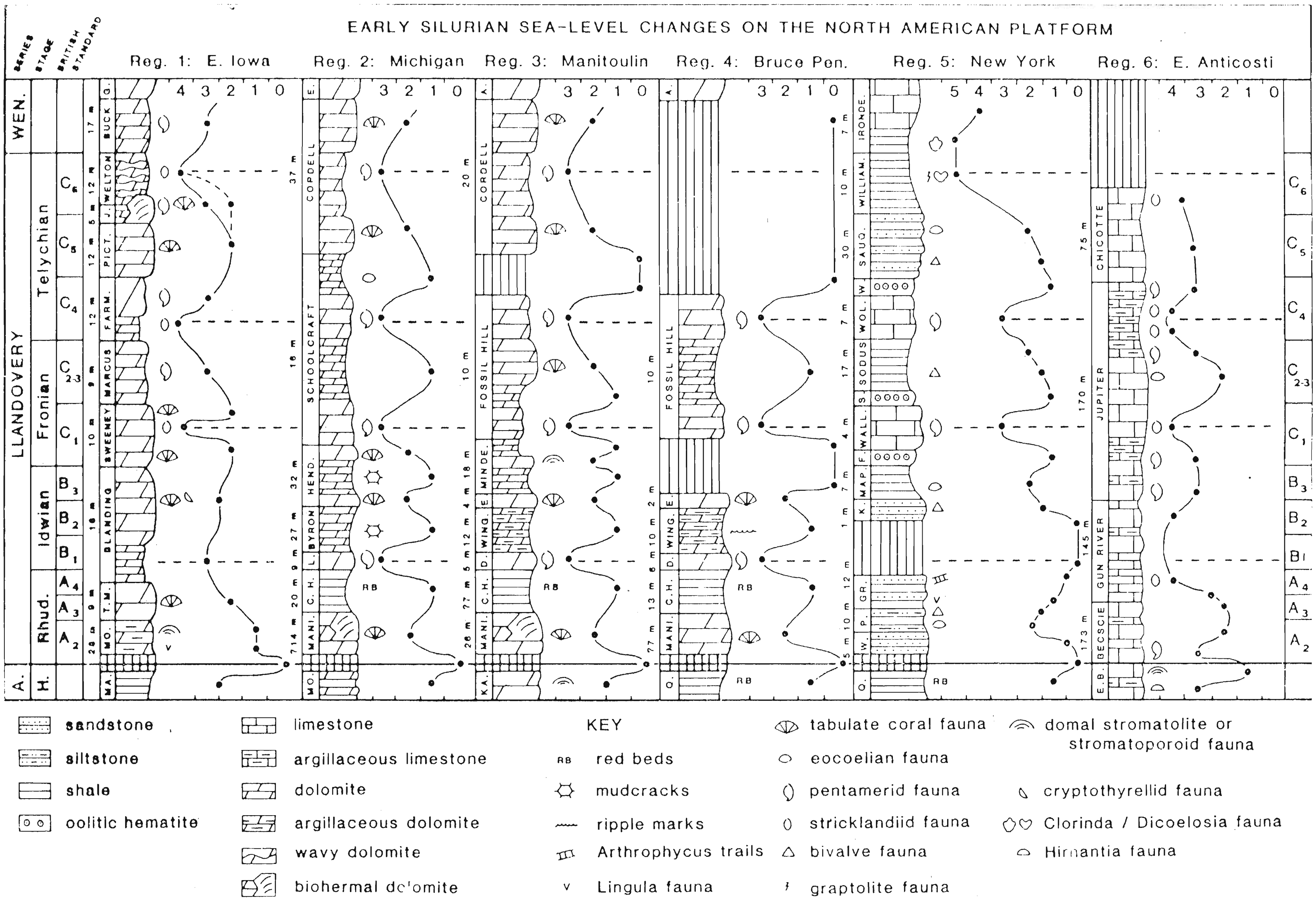


Figure 13: Sea level curves showing relative changes in water depth on the North American Platform. Horizontal dashed lines indicate stratigraphic positions of the four main sea level peaks (Johnson et al., 1985).

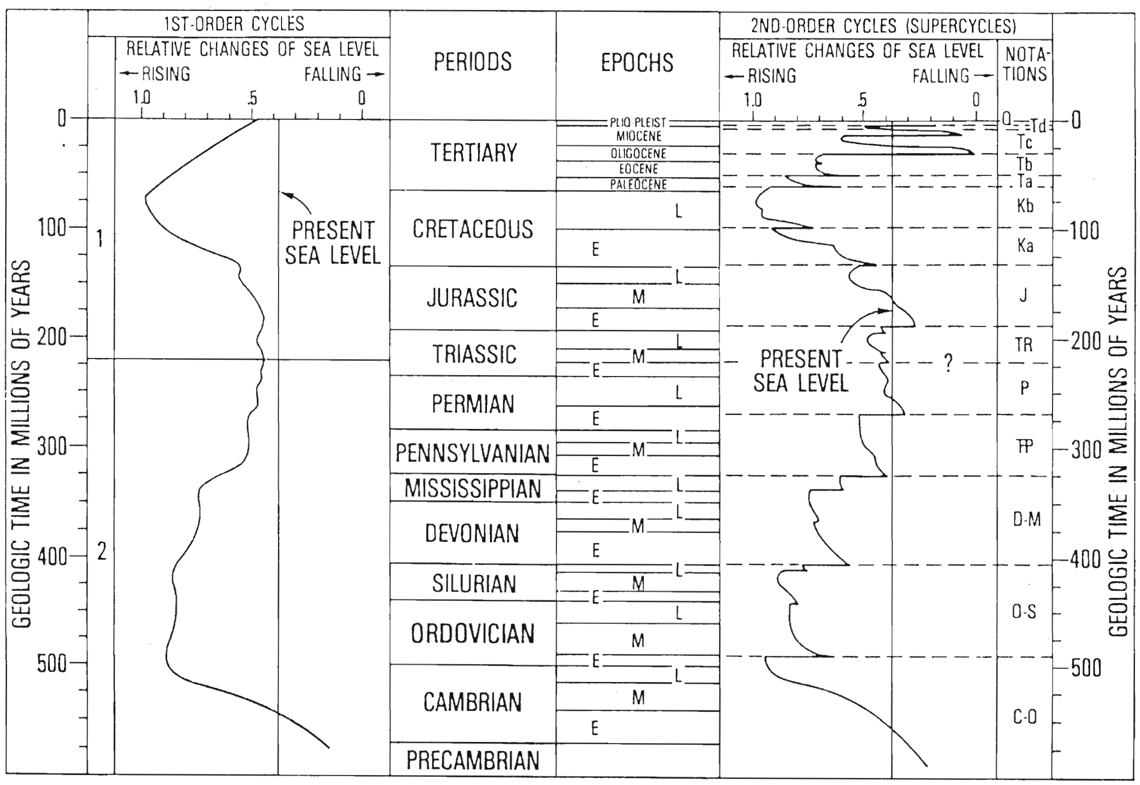


Figure 14: Curves of Vail et al. (1977) depicting first and second order global cycles of relative change of sea level during Phanerozoic time.

GEOLOGY OF THE CATARACT GROUP AND ASSOCIATED FORMATIONS

In the Late Ordovician - Early Silurian, the Lake Erie area was situated on the edge of the Appalachian Basin on the southeastern flank of the Algonquin - Findlay Arch complex. The arch complex, although significant to the development of the Cataract Group, was for the most part quiescent during this period (Middleton, 1987; Figure 4). The arch was primarily submerged as there is little geological evidence suggesting subaerial exposure and erosion. Consequently, the Lake Erie study area was a zone of interfingering of deposition from both the Michigan Basin to the northwest of the arch complex where deposition was primarily carbonates, and the Appalachian Basin to the southeast where siliciclastic sediment was derived from a source area to the east and southeast.

Much of the previous work on the Cataract Group is based on outcrop studies, primarily along the Niagara Escarpment. Subsurface work has been limited to unpublished B.Sc. theses, commonly on just one gas pool (Cleland, 1987; Lesage, 1988; Millest, 1988; Rouble, 1991) and a few unpublished M.Sc. theses (Writt, 1977; Rafalowski, 1982). Much of the subsurface work has been produced 'in house' by oil companies or consultants which do not publish their work because of confidentiality agreements.

The Queenston Formation (Grabau, 1909) is predominantly a red shale averaging 200 metres in thickness in Ontario and up to 500 metres in New York and was deposited during the Ashgillian (Zerrahn, 1979). Early authors suggested that the Queenston Formation was deposited in a deltaic setting (Dennison, 1976; Liberty, 1969) and it is commonly referred to as the Queenston 'delta'. However, recent studies (Brogly, 1984) suggested that this is not the case because the formation lacks distributary channels which are diagnostic for deltaic settings and it also has evidence of many brief marine incursions. It has recently been interpreted as a sequence of muds deposited very close to sea level on a broad, supratidal plain, that was roughly the terrigenous equivalent of a clastic coastal sabkha (Middleton, 1987).

Lying unconformably above the Queenston Formation throughout most of the study area is the Whirlpool Sandstone (Grabau, 1909) which is the basal member of the Lower Silurian Cataract Group. This formation is defined petrographically as a very fine- to fine-grained subarkose to quartz arenite. The contact with the Queenston Formation is a mud-cracked, knife-sharp surface, that is both regionally and locally flat-lying (Rutka *et al.*, 1991; Sanford, 1969). The Queenston - Whirlpool contact shows no evidence of major erosion and is generally considered to be a disconformity of unknown duration across the Ordovician - Silurian boundary. North of Hamilton, the Whirlpool Sandstone passes upwards into the Manitoulin Dolomite and, to the south, into the Cabot Head Shales. It forms an irregular sheet of sandstone with a maximum thickness of nine metres in the east and southeast which thins and pinches out to the west and northwest where it is replaced by the Manitoulin Formation. It extends southward in the subsurface of New York, Ohio, and Pennsylvania, and laterally merges with the Grimsby Formation, passing into the Tuscarora Formation (Piotrowski, 1981; Laughrey, 1984).

The Whirlpool Formation has been extensively studied, both in outcrop and subsurface as well as petrographically and sedimentologically (Bolton, 1957; Martini, 1971; Piotrowski, 1981; Martini and Salas, 1983; Cheel *et al.*, 1994; others). Recent work (Middleton *et al.*, 1983; Middleton *et al.*, 1985; Middleton *et al.*, 1987; Cheel *et al.*, 1994) suggests that the formation consists of two units: an upper marine unit that was deposited in a nearshore, wave-influenced environment and a lower unit that formed in a braided fluvial environment.

Beyond the subcrop limits of the Whirlpool Formation and into the Michigan Basin, the Manitoulin Formation (Williams, 1913) forms the basal strata of the Cataract Group. Where the Whirlpool Formation is not present, the Manitoulin Formation unconformably overlies the Queenston Formation. The formation is present in subsurface in much of southwestern Ontario and pinches out along a line running roughly from Stoney Creek in southern Ontario to northwestern Ohio (Sanford, 1969). It ranges from approximately three to eight metres in thickness where the Whirlpool Formation is present but increases to 25 metres in extreme southwestern Ontario, where the Whirlpool is absent (Brigham, 1971). The Manitoulin is primarily an argillaceous dolomite with numerous shale partings and is abundantly fossiliferous. Common phosphate nodules and pebbles in the eastern sections were reported by Fisher (1954).

The argillaceous dolomites of the Manitoulin, or the Whirlpool Formation where no Manitoulin is present, pass vertically and conformably into the deeper water facies of the Cabot Head Formation. Beyond the subcrop limits of the Whirlpool Sandstone, the Cabot Head Formation conformably overlies the Manitoulin Dolomite. The Cabot Head is present throughout southwestern Ontario, the eastern and northern portions of the Michigan Basin and parts of western New York. The unit reaches a maximum thickness of approximately 40 metres in the subsurface and thins to approximately 15 metres over the Algonquin Arch (Sanford, 1969). To the west of the study area, in the central portions of the Michigan Basin, the Cabot Head has a reciprocal thickness with the Manitoulin Dolomite and eventually pinches out towards the Cincinnati Arch region, where it is replaced by the carbonates of the Alexandrian Series (Catacosinos *et al.*, 1990).

The Cabot Head Formation varies in lithology and consists primarily of gray shales interbedded with thin, very fine grained orthoquartzitic sandstone (Sanford, 1969). The sandstones are commonly only centimetres thick but locally increase to nearly a metre in thickness in the upper half of the formation. They also tend to become more numerous towards the east and southeast where, in some locations, the formation is primarily argillaceous sandstones. In the lower portions of the formation, some beds of argillaceous and/or sandy fossiliferous dolomite and limestone are present, commonly from one to ten centimetres in thickness (Sanford, 1969).

Conformably above the Cabot Head Formation is the Grimsby Formation (Williams, 1914). Fisher (1954) noted that the formation extends along the Niagara Peninsula from Medina, New York, where it is 20 metres thick, to Clappison Corners, Ontario, where it pinches out. He also noted that it was the sole Cataract unit which extended into central New York as far east as Oswego. In subsurface, Sanford (1969) showed that it continues southward beneath western Lake Erie. Near Rochester, New York, the Grimsby Formation becomes indistinguishable from the orthoquartzitic sandstones of the underlying Cabot Head Formation (Brett *et al.*, 1991).

Fisher (1954) discussed the deposition of the Cataract Group and suggested that paleoenvironmental conditions were similar to those that existed during the deposition of the Queenston Formation which was believed to be a deltaic deposit at that time. It was suggested that the Cataract Group 'delta' was only the closing phase of deltaic sedimentation initially begun in Richmond time. It was deposited during a period of regression similar to that thought to have occurred during the development of the Queenston 'delta' but with coarser material. Fisher (1954) also suggested an eolian origin for the Whirlpool Formation with windblown sand spreading over the exposed Queenston mud flats. He suggested that a marine transgression from the southwest then reworked the eolian deposits. Deepening seas then led to a replacement of sand deposition by the carbonates of the Manitoulin Formation and the marine shales of the Cabot Head. The Grimsby Formation was interpreted as coarse clastics deposited in shallow and energetic flows, due to the presence of cross-bedded sanstone and intra-formational conglomerates. The Thorold Formation was thought to represent the end of deposition of the Cataract Group because the formation was recognized as a relatively clean sandstone composed primarily of reworked Grimsby. Fisher (1954) also noted the abundance of accessory minerals within the Thorold Formation and suggested that this was a lag concentrate which was brought about by *in situ* reworking caused by a retreating sea and a decrease in the amount of siliciclastic material brought into the area.

Sanford (1969) suggested that a gradual regression of the Cataract Sea resulted in major facies changes in southwestern Ontario which led to the deposition of coarse redbed clastics of deltaic origin (Grimsby) within the Appalachian Basin, gradually extending into the Niagara area and eastern Lake Erie. These pass laterally west into the normal marine shales of the Cabot Head Formation and eventually the carbonates of the Michigan Basin as the volume of siliciclastic material decreased away from the source area to the east.

Rather than including the Thorold Formation within the Cataract Group, Sanford (1969) proposed that the sandstone represented the basal transgressive facies of the Reynales - Irondequoit succession. He suggested that because the normal marine orthoquartzitic sandstone of the Thorold Formation differed from the redbed deltaic deposits of the Grimsby Formation, that it should be considered as part of the Clinton Group rather than the Cataract Group. He also suggested that because of the irregular distribution and texture of the Thorold, at least part of it had been scoured from the subjacent Grimsby during the transgression. Confusion of where to place the Thorold Formation in the stratigraphic column persists to this day, as many charts indicate it as being part of the Cataract Group (Duke *et al.*, 1991) whereas others include it as part of the Clinton Group (Brett *et al.*, 1991).

The notion that the Cataract Group, particularly the Grimsby Formation, was deposited in a deltaic environment persisted in the literature for quite some time. Martini (1971), based on his outcrop study of the Niagara Escarpment, interpreted the sedimentology of the Cataract Group as a mixed depositional environment of deltaic and shallow marine sedimentation. He suggested that the growth of the deltaic sequence was due to shifting deltas over time, as in the recent Mississippi delta. Martini (1971) also suggested that the combination of a relatively slow rate of clastic input, a shallow sea, and a very slow rate of subsidence yielded a complex interfingering of deltaic topset deposits with prodelta and/or interdeltaic deposits.

Martini (1971) described the eastern portions of the escarpment and attributed the topset deposits to shoreline environments characterized by channel sedimentation, beaches, and tidal flats, and high tidal flats to floodplain settings. The prodelta portion of the delta, or the more open-marine environments, are represented by the dolomites, shales and silty sequences further to the west in the vicinity of Hamilton.

In the eighties, the delta interpretation of the Cataract Group was questioned. Duke (1982) suggested that the Grimsby and Thorold formations were deposited as a storm-dominated, shallow-marine, prograding shoreline sequence. This was based in part upon the presence of abundant hummocky cross-stratification within the succession. He observed the following vertical series of facies: a central basin carbonate overlain by distal-offshore shale which was overlain in turn by interbedded shales and storm-deposited offshore sandstones. Overlaying these are nearshore sandstones. Hummocky cross-stratification, offshore bar-like features and submarine channels are associated with the interbedded shale storm-deposited offshore sandstone facies. The bars are oriented parallel to the shoreline (roughly N-S) and the channels, which are oriented approximately perpendicular to the shoreline, cut through the offshore bars. Duke *et al.* (1991) suggested that the shoreline was oriented NNE-SSW and was an intertidal sand flat dissected by nearly shore-normal estuaries and tidal channels. A sharp transgression resulted in the deposition of the Neahga Shale and the Reynales Formation.

Duke and Brusse (1987) also questioned the deltaic depositional model. They observed laterally extensive coarsening upwards sequences that they attributed to shelf aggradation/shoreline progradation during periods of stable sea level. In addition, they suggested that in the very shallow, gently sloping basin, a relatively rapid, rather minor drop in relative sea level occurred. This resulted in the subaerial exposure of large areas of previously deposited proximal offshore shelf deposits, causing the irregular erosion of these coarsening upwards sequences. Increased coastal-plain gradients caused the incision of relatively small, closely spaced, fluvial channels across the exposed shelf deposits. During the subsequent transgression, the remaining channels were filled by marine deposits; the most distal reaches of these channels were filled entirely by marine deposits, primarily mud.

Duke and Fawcett (1987) suggested that depositional cycles within the Cataract Group were recognizable by abrupt breaks in vertical thinning/fining or thickening/coarsening trends. The cycles are partly defined by regionally extensive erosional disconformities and cycle boundaries are punctuated locally by channels.

The various features of cycle boundaries and their associated channels are consistent with their inferred origin as discussed in Duke and Brusse (1987). They suggested that tidal and/or estuarine channels were incised into offshore subtidal deposits as extensive areas of the shelf were partially or completely exposed during the shifting of the shoreline toward the west. The eastern areas were more completely exposed to tidal, estuarine, and/or fluvial incision over longer periods during the regressive events and was also subjected to periods of non-deposition or erosion. It was also suggested that the outcome was a thinner but coarser deposit in the east with material being distributed seaward to the west and a thicker but finer deposit in the west. The longer exposure times in the east also resulted in more extensive lateral migration and increased size of the channels.

Duke (1987) also questioned the use of colour to delineate many of the formation boundaries of the Cataract Group. The Cabot Head - Grimsby Formation boundary was usually picked by earlier workers, especially by industry, according to where the deep red colour first appeared. Duke (1987) demonstrated that the colour variations from red to light gray and green, and dark gray to black are controlled by variations in the oxidation state of iron-rich cements and the relative abundance of organic matter within the sediments. The colours are therefore diagenetic in origin and cut across an independent set of physically correlative sedimentary and stratigraphic textures and facies. He proposed that the formation boundaries be set, not by colour changes, but by established lithological and sedimentological parameters.

Duke *et al.* (1991) described the lower part of the Cataract Group as being dominated by interbedded mudstones and thin wave-rippled and hummocky cross-stratified very fine grained sandstones. The upper part was dominated by a thick, trough cross-bedded, sheet-like fine to medium grained sandstone. It was suggested that paleoflow data, trace and body fossils, and stratification point to the sequence being a vertical transition from a subtidal, storm-dominated, open epicontinental sea depositional environment to a tide-dominated, wave-influenced shoreline environment.

Duke *et al.* (1991) also suggested that several smaller shoaling sequences could be identified, each separated by erosional disconformities. These two different scales of depositional cyclicity were attributed to episodic aggradation and shoaling during the episodic west-northwestward progradation of the shoreline. The episodes of progradation were interrupted by rises in relative sea level, forming the para- and disconformable deepening surfaces between the smaller shoaling sequences. Associated with the erosional boundaries of the small sequences are large sinuous channels oriented nearly normal to shore. The channels were deflected slightly from shore-normal by strong wave-induced longshore drift to the NNE and are incised into and overlain by mudstones and thin hummocky cross-stratified sandstones deposited offshore in an open marine, subtidal, storm-dominated setting. The presence of these channels just below sequence boundaries places them in the shallowest portion of the smaller sequences with fossil evidence suggesting a restricted marine environment.

For a modern analog for the Cataract Group, Duke *et al.* (1991) suggested the coast of German Bay (Helgoland Bight) of the North Sea (Figure 15) which presents even the same orientation of the shoreline and channels as the coast of the study area in Lower Silurian time. The coastline is a series of tidal channels and estuaries (Reineck and Singh, 1975, 1980) very similar to those interpreted in the Grimsby Formation on the basis of outcrop along the Niagara Escarpment. The estuaries bring sediment to the shoreline from several major rivers and the thalwegs of the channels are incised to shallow subtidal depths. Widths of the channels increase seaward and, although wider than those of the Cataract Group, are similar in vertical thickness to the multi-story channel complexes observed in the Niagara Gorge. Duke *et al.* (1991) suggested that because the German Bay channels display multiple, subparallel thalwegs and that the isolated Cataract Group channels were compacted and subjected to transgressive erosion of their upper

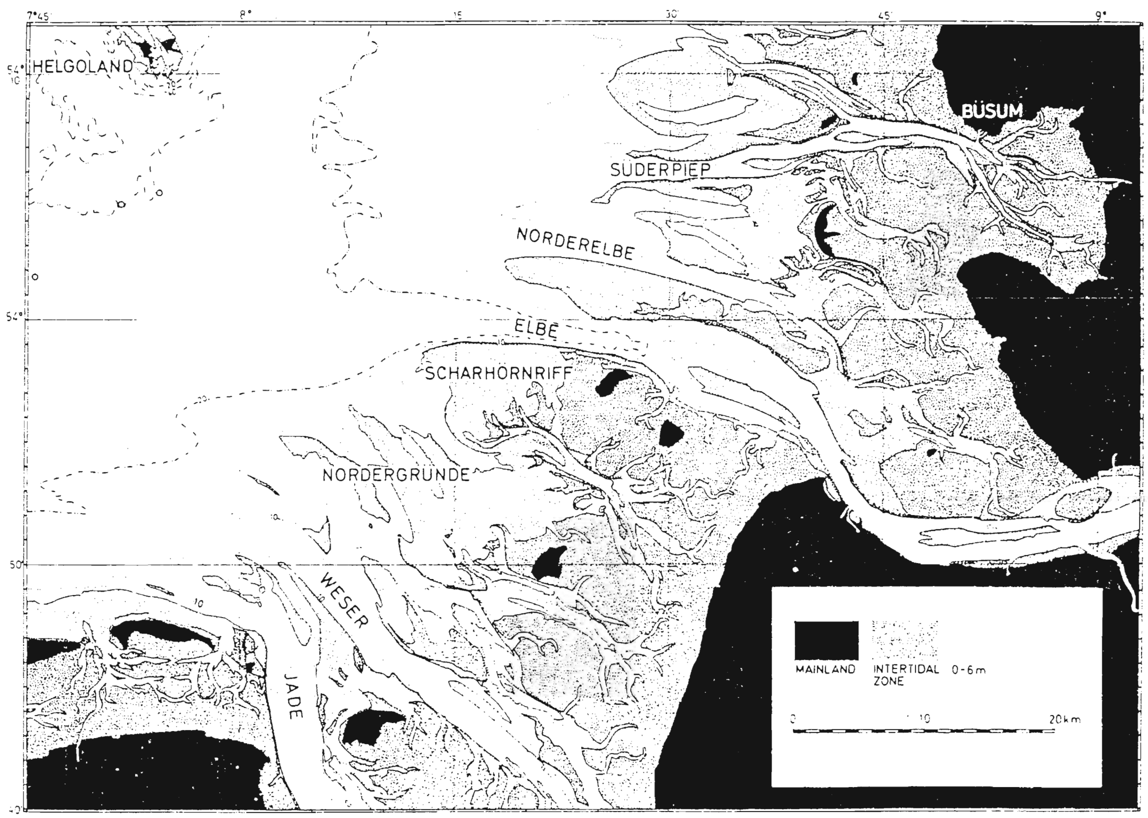


Figure 15: Map of tidal channels and three estuaries (the Jade, Weser and Elbe) along the sandy intertidal flats of the German Bay, North Sea. Duke (1991) suggests that this is a modern analog for the Cataract Group (Reineck and Singh, 1975).

portions, that the tidal channel systems in the two depositional settings may have been on a similar scale. The thalwegs of the modern channels and estuaries are mantled by coarse grained material along with shelly debris similar to the erosional lags found in the Cataract Group (Reineck and Singh, 1975, 1980). The sandy channel fills are composed almost entirely of medium-scale trough cross-bedding exhibiting reversing flow directions, with thin layers of shells and horizontal-laminated fine sand. Some channels are dominated by muds where the sands have bypassed the channel.

Offshore from the coastal channels, the deeper subtidal channels are incised into muddy basinal sediments and sands. Sharp based medium to very fine grained sands interbedded with muds are deposited in subtidal depths seaward of the tidal channels and estuaries (Reineck and Singh, 1975, 1980). The sands thin and fine basinward and are eventually flushed into the North Sea by offshore-directed storm-induced coastal downwelling, commonly amplified by ebb-tidal currents or river flood-waters originating from channel mouths. Cores from these offshore sand beds display horizontal lamination, inferred hummocky cross-stratification, and abundant wave formed ripples (Aigner and Reineck, 1982). The German Bay offshore closely matches that of the Grimsby Formation observed by Duke *et al.*, (1991) in outcrop along the Niagara Escarpment from east to west.

TRACE FOSSILS AND THE CATARACT GROUP

Pemberton (1979) identified 27 ichnogenera from the Thorold Formation in outcrop along the Niagara Escarpment. He suggested that these ichnofossils were indicative of a shallow-water, nearshore environment and were of the *Skolithos* and *Cruziana* ichnofacies. Further, the trace fossils were divisible into four distinctive assemblages. Assemblage one, restricted to western New York State, was indicative of a low energy, nearshore environment. Assemblage two, further to the west, was characteristic of the *Skolithos* ichnofacies and indicative of a shoreface environment. Assemblage three consists of a mixed ichnocoenoses which contains elements of both the *Skolithos* and *Cruziana* ichnofacies, suggesting a lower shoreface to offshore environment. Assemblage four is a continuation of the *Cruziana* ichnofacies and suggests offshore deposition. Assemblage three and four were located further to the west along the Niagara Escarpment.

Pemberton (1979) suggested that the assemblages could be differentiated based on lateral variations and that these variations corresponded quite closely to the observed lateral variations in sedimentary properties observed by Martini (1966)

PALEOPALYNOLOGY AND THE CATARACT GROUP

Strother and Traverse (1979) identified apparently non-marine, spore-like micro-fossils from the Lower Silurian Tuscarora Formation of Pennsylvania, correlative in age to the Grimsby Formation of southern Ontario. This may indicate one of the earliest indications of the evolution of land plants. The suite of microfossils reported by Gray *et al.* (1982) and reported as of Late Ordovician age (Caradocian - Ashgillian) seems identical to that of the Early Silurian of Pennsylvania and Virginia (Strother and Traverse, 1979; Pratt *et al.*, 1978). Miller and Eames (1982) also recovered acritarchs from the Cataract Group in the Niagara Gorge near Lewiston, New York and reported similar spore-like microfossils, suggesting a similarity of spore-like palynomorphs between the Tuscarora and the Whirlpool Sandstone as well as the Cabot Head Formation.

FACIES OBSERVATIONS

Eighty-five measured sections of core were used to define facies based upon lithology, sedimentary structures, fossil and trace fossil content, and palynology. Well logs were used on a limited basis to observe general features of each of the facies but each facies was not delineated across the study area.

Five facies are defined from the cores. Facies A comprises the Cabot Head Formation and is commonly found at the base of the cores, Facies B is commonly located at the base of the Grimsby and is normally equivalent to the Lower Grimsby Formation, Facies C is equivalent to the Middle to Upper Grimsby Formation, and Facies D is equivalent to portions of the Upper Grimsby Formation and all of the overlying Thorold Formation. Facies E is normally at the top of the core sections and consists of the lower portions of the Reynales Formation. Further subdivision of the facies was not performed as this study is a regional overview of the Grimsby and Thorold formations in subsurface Lake Erie. The five identified facies provide a basic lithologic subdivision of the core sections which are recognizable from core to core. The variabilty of each of the facies from well to well makes correlation and mapping difficult. Subdivision of each of the facies using the available well logs and further cores goes beyond the scope of this thesis.

FACIES A

Facies A is predominantly composed of, dark gray, fissile shale and buff coloured, silty to very fine grained sandstones (Figure 16); the shale makes up approximately 65-70 per cent of the facies and normally exhibits horizontal to slightly wavy bedding. Facies A is present only in the Cabot Head Formation. The siltstones and sandstones are normally centimetres in thickness, but can be up to several decimetres thick, are quartzose and have subrounded, moderately sorted grains with primary sedimentary structures such as horizontal laminae and current rippled cross-laminae. Thicker sandstones occur towards the top of the Cabot Head in many sections and are described below. The thin sandstones are commonly weakly bioturbated by *Teichichnus* and *Planolites* with the burrows extending into the underlying shales and infilled by sand. In the absence of bioturbation, the boundaries between the shales and sandstones are sharp. Commonly, at the base of the thinner sandstones is a thin zone of fossil fragments - bryozoans, crinoids, brachiopods and other shell fragments. In some cores, the dark gray colour of the shales and the buff colour of the sandstones has been replaced in the upper part of this facies with a red to dark red staining.

Facies A also contains highly fossiliferous, calcareous to dolomitic, very fine to coarse grained sandstones (Figures 17, 18). Very fine to coarse grained quartz sand in a matrix of clay and hematitic cement are the main components of these beds which are sharply bounded on both the top and bottom. Internal stratification is rare in these beds, but in the case of one very thick bed of two metres, cross-bedding is clearly present. The coarse grained beds also contain abundant reworked fossil debris, most commonly bryozoan fragments, generally lying horizontally, as well as brachiopod shells, crinoid fragments, shale rip-up clasts and phosphatic pebbles. Normally, the beds are centimetres to decimetres thick and are a dark red colour.

In many cores, a relatively thick (1-2.5m) sandstone body is present, normally in the upper portions of facies A. Like the thinner sandstone beds, it is primarily a silty to very fine grained, quartzose, cream coloured sandstone. This sandstone is distinct by the abundant dish structures in many cores (Figures 19, 29a, 30b) and can be correlated from core to core and in well logs over wide portions of the study area. Both the upper and lower boundaries of the sandstone are abrupt. The sandstone occurred over most of the

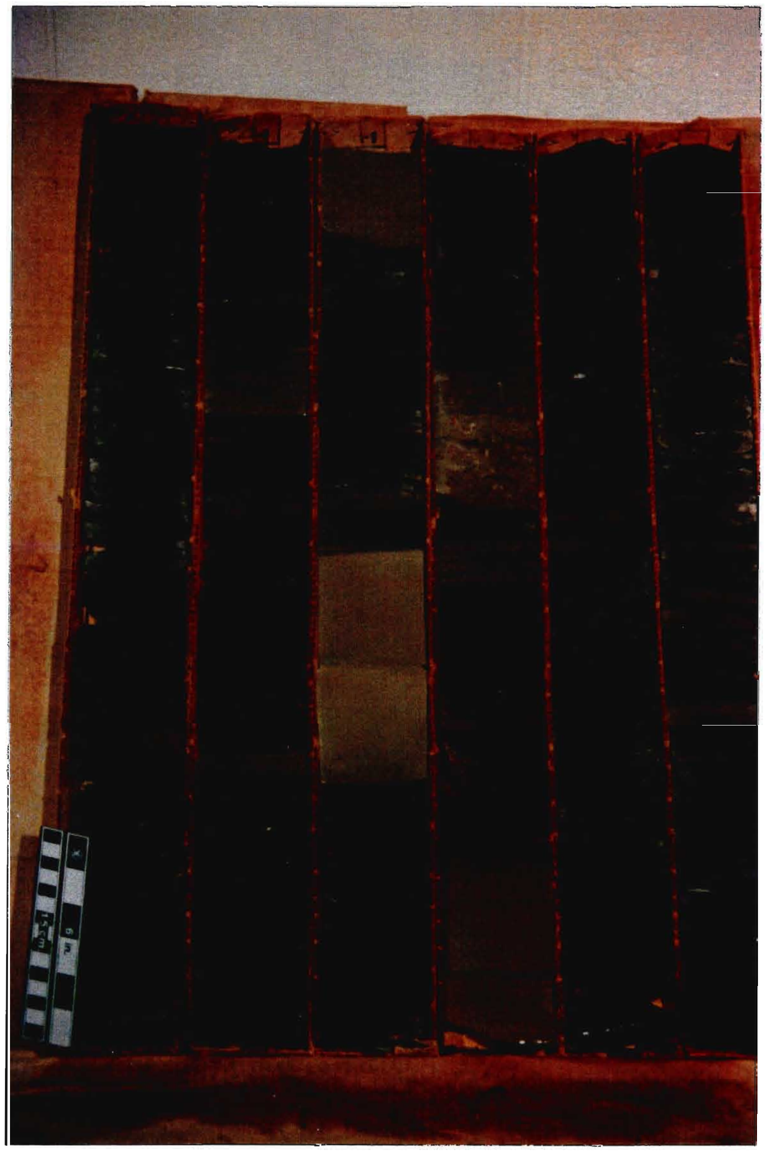


Figure 16: Facies A, Consumers 13169, Block 99-K. This is a normal appearance of the facies, primarily gray shale with thin, buff coloured sitstones and sandstones of the upper Cabot Head Formation. The scale is 15 cm long and located at the bottom of the core and the top of the core is in the far upper right corner.

Figure 17: Hematitic, fossiliferous bed from Consumers 13224, Block 121-A. The whitish bryozoan fragments scattered throughout the zone are easily distinguishable. Scale is at bottom of core.

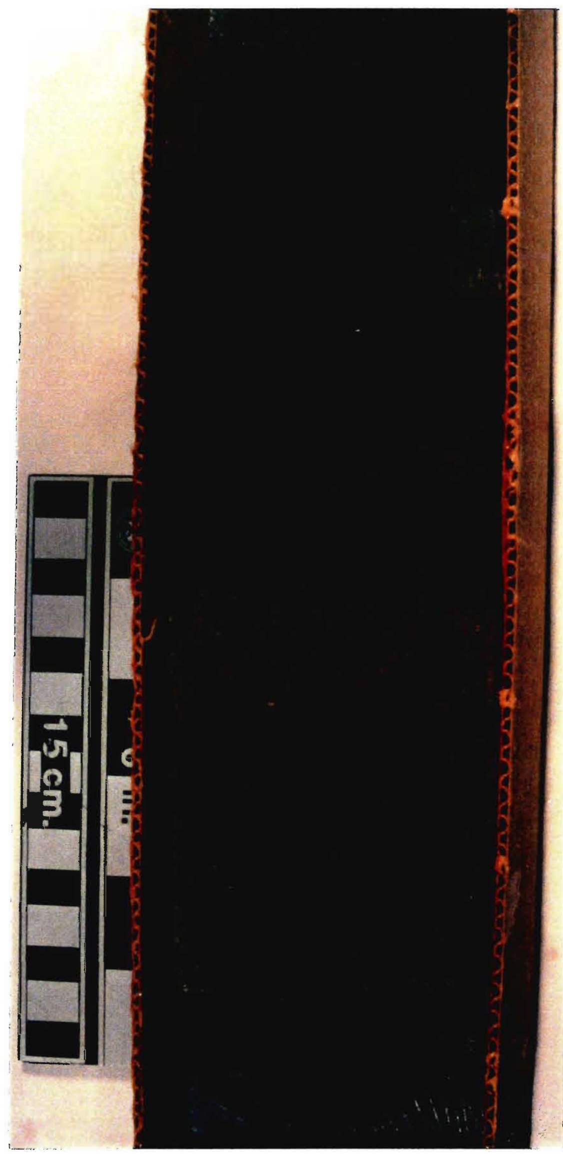


Figure 18: A mostly unoxidized fossiliferous bed from Consumers 13224, Block 121-A. Scale is at bottom of core.

study area and, in some cases, is divided into two distinct metre thick units separated by a sharply bounded shale bed approximately one to two metres in thickness. In rare instances, fossil debris consisting of bryozoan, crinoid and brachiopod fragments, occurs at the basal contact of the sandstones and shales and is commonly up to a few centimetres thick. Where no dish structures are present, horizontal, argillaceous laminations dominate and, in some cores, the sandstone exhibits hummocky cross-stratification (HCS; Figure 20). The HCS is small scale. One core (Consumers 13221, Block 123-O) exhibits hummocky cross-stratification grading upwards into parallel laminations and then dish structures. In another core where HCS is well developed, the sandstone has light brown oil staining although the porosity of the unit is poor to tight. In the farthest northern and western margins of the study area, the sandstone is replaced by several thin, discreet sandstone beds that are centimetres thick, separated by thin (up to several centimetres) sandy, shale layers.

FACIES B

This facies is a fine to medium grained quartz arenite that normally fines upwards. The sandstones are predominantly red but are locally mottled light gray (Figure 21). The sand grains are principally quartz with few lithic fragments, subangular to subrounded, moderately to well sorted with a siliceous matrix. A coarse basal lag is common to this facies, normally less than fifteen centimetres thick, and typically includes abundant subangular to rounded rip-up mud clasts up to several centimetres in diameter, *Lingula* shells, and phosphatic pebbles (Figure 22). It normally is present at the boundary between the Cabot Head Formation and the Grimsby Formation. However, several lag deposits can occur vertically within a core (e.g. Figure 25) with the lower most one representing the basal unit of the Grimsby. Where a basal lag is present, it is normally overlain by a

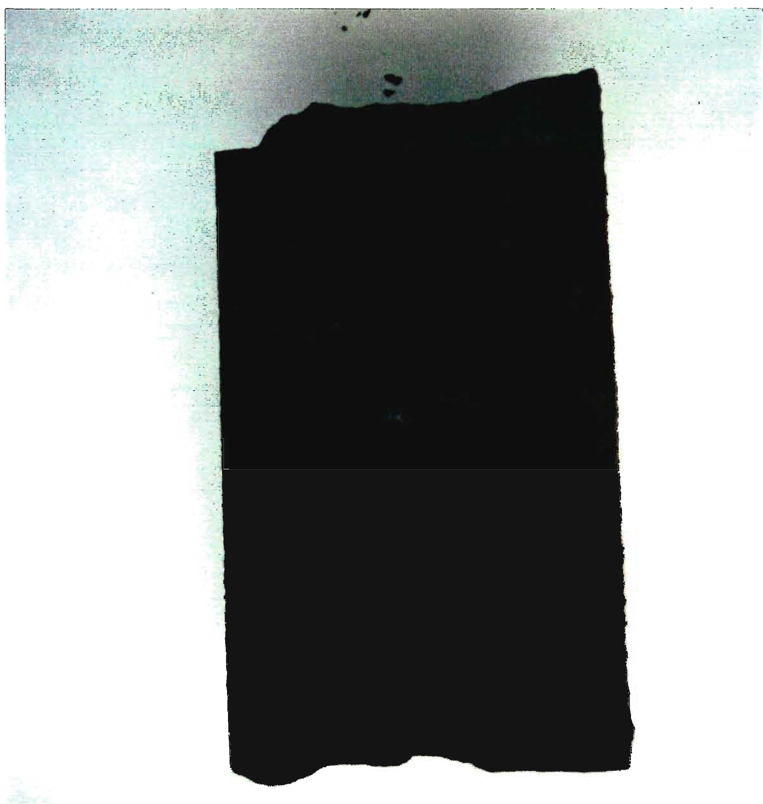


Figure 19: Dish structures common to sand body in upper portions of Facies A, Consumers 13221, Block 123-O. Core is dark brown due to oil staining.

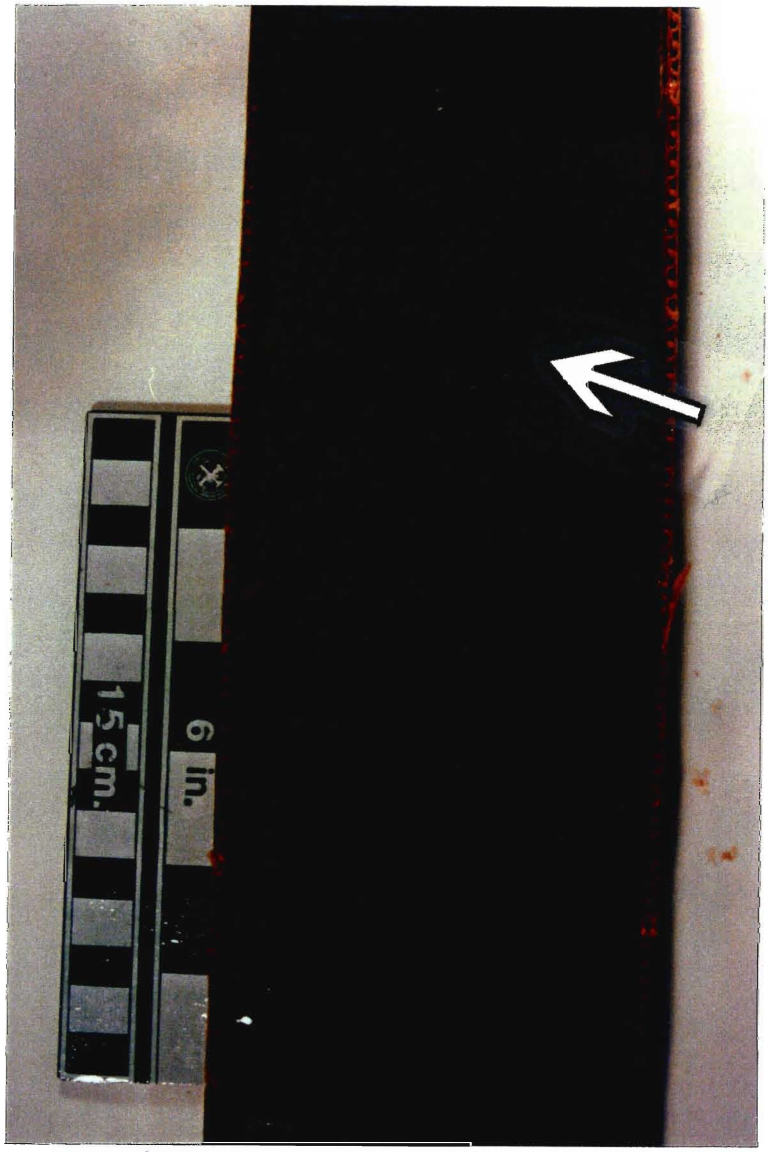


Figure 20: Hummocky cross-stratification (HCS), indicated by arrow, in sand body, Consumers 13169, Block 99-K. The HCS bedding was observed in the same sand body that commonly exhibits dish structures. Scale is at bottom of core.

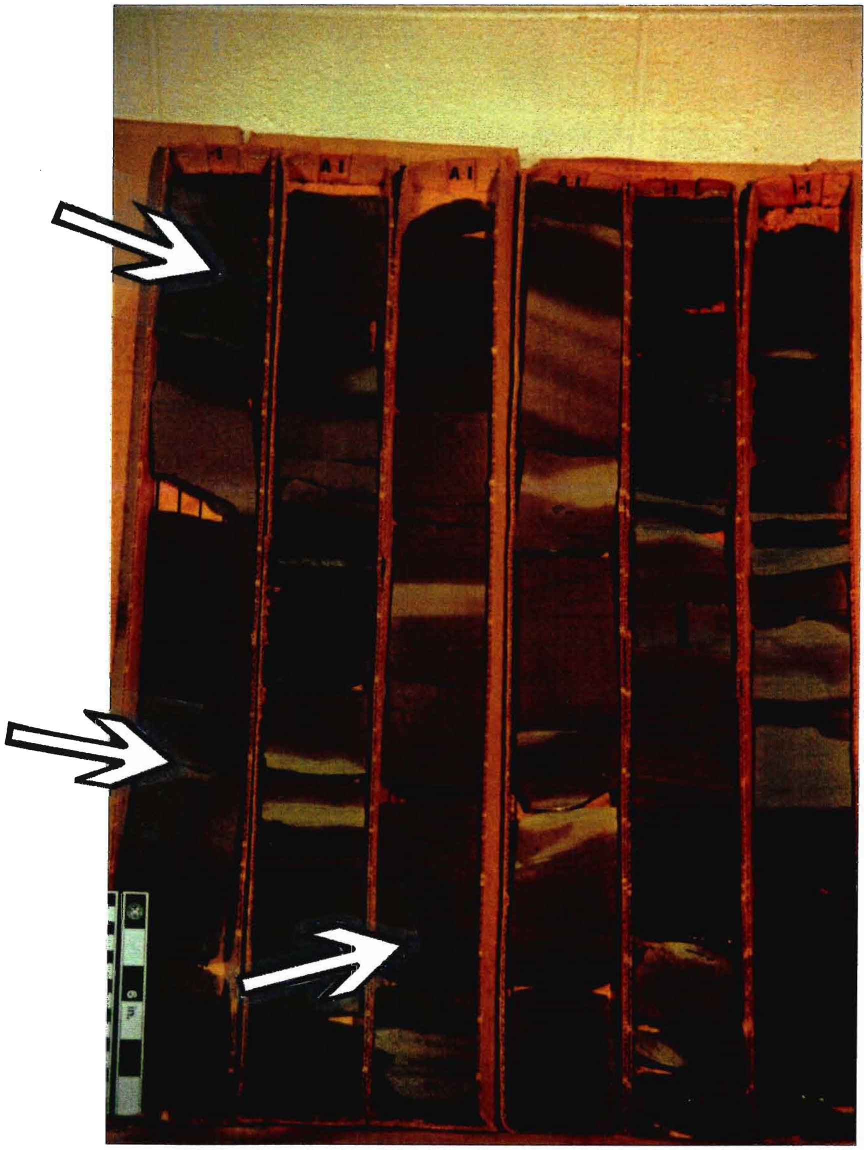


Figure 21: Facies B, Consumers 13224, Block 121-A. The red and gray mottling is common. The zone fines upwards towards the shale beds (dark red, right) which are part of Facies C. The high angle laminations observable in the core to the left grade to low angle laminations to the right. Scattered mud clasts (arrows) are also observable. The scale is 15 cm long and is at the bottom of the core with the top being in the upper right.

Figure 22: Common lag deposit at base of Facies B, Consumers 13197, Block 153-H. The deposit includes Lingula shell fragments, phosphatic nodules (arrow) and rip-up mud clasts. In some other cores, the rip-up mud clasts can be much larger but the lag deposits themselves rarely exceeded fifteen centimetres in thickness. Scale is at bottom of core.

zone of high angle cross-bedding. The high angle cross-bedding is commonly associated with mud drapes along the bedding surfaces that define the foresets and the troughs of cross-beds. Mud couplets occur along some of the foreset beds and consist of two thin mud drapes alternating with a thin and thick layer of sand (Figure 23a, b). Mud couplets consist of thin layers of sand 2 to 3 mm in thickness and thick layers of sand 8 to 12 mm in thickness. Low angle cross-bedding normally overlays the high angle cross-bedding. Cross-bed sets range in thickness from 4 to 30 cm. The low angle cross-bedding is commonly found in the upper portions of the facies and is composed of finer grained sands than the high angle cross beds, coinciding with the general fining upwards trend found in most cores for this facies.

The facies may contain rare *Lingula* shell fragments and elongated, subangular to rounded rip-up mud clasts of up to one centimetre in diameter, commonly oriented along argillaceous laminae which define the cross-beds. In some cores, high angle cross-bedding is overlain by a massive sandstone up to 1.5 metres thick (Figure 24) which in turn is overlain by low angle cross-bedding. Bioturbation is negligible within this facies and when present (primarily identified as *Teichichnus* and *Planolites*) is associated with very rare mudstones.

The lower boundary of Facies B is normally sharp and the upper boundary is normally gradational with an increase in the frequency of shale partings and thin shale beds (an indication of the general fining upwards trend) and a change in bedding features from predominantly high angled or low angled cross-bedding to predominantly rippled cross-laminae.

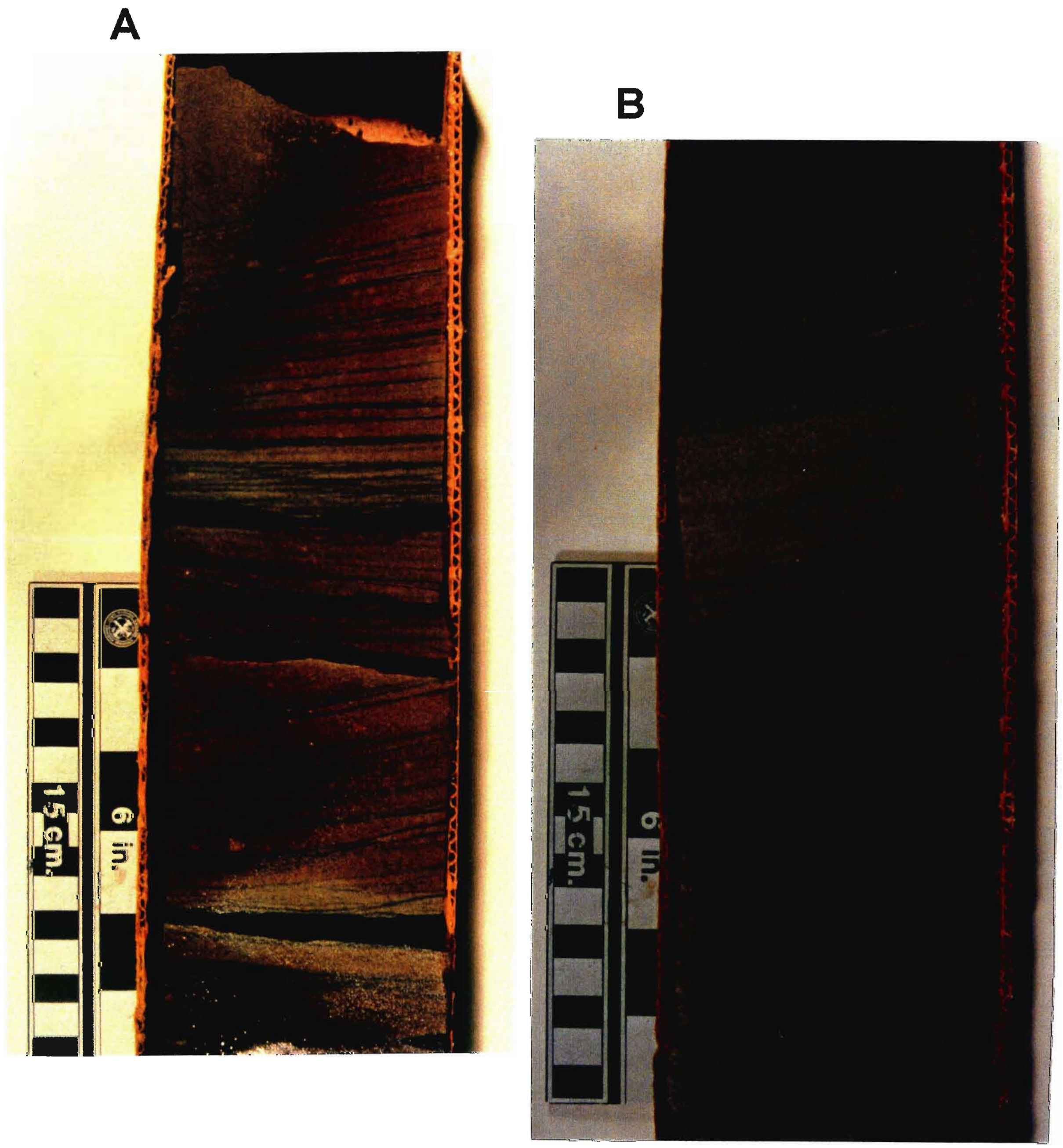


Figure 23a, b: From Facies B, two examples of mud couplets observed from Consumers 13197, Block 153-H. Scale is at bottom of both cores.

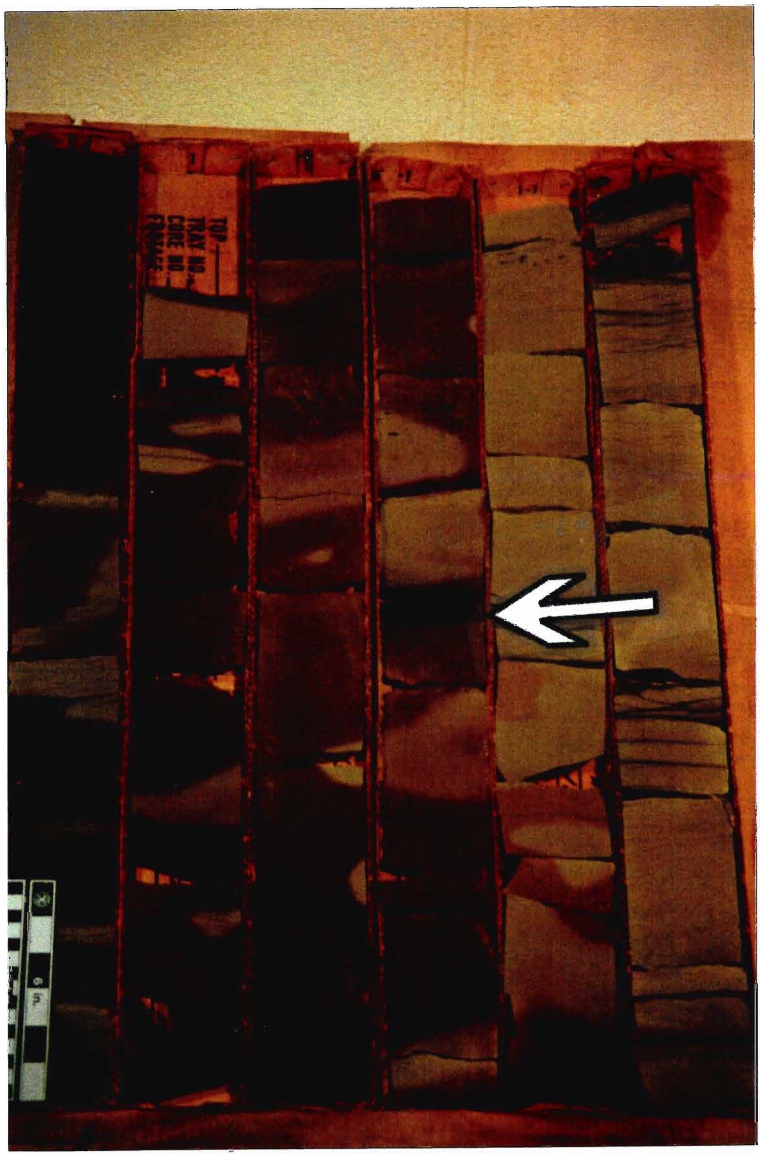


Figure 24: Consumers 13153, Block 122-J, showing Facies B (second to fourth trays from left). Massive, non-bedded sandstone can be found in third tray from left. Note the mottling. Facies B - C boundary is in the upper half of the fourth tray from the left (arrow). The scale is 15 cm long and located at the bottom of the core and the top of the core is in the far upper right corner.

Well Name: Consumers 13237
Block Number: 123-F

Latitude: 42 28' 37.17" N
Longitude: 80 39' 24.85" W

Cored Interval: 1567 - 1612 ft.
477.6 - 491.3 m

K.B. Elev.: 619 ft. 188.7 m
Pet. Res. Core No.: #191

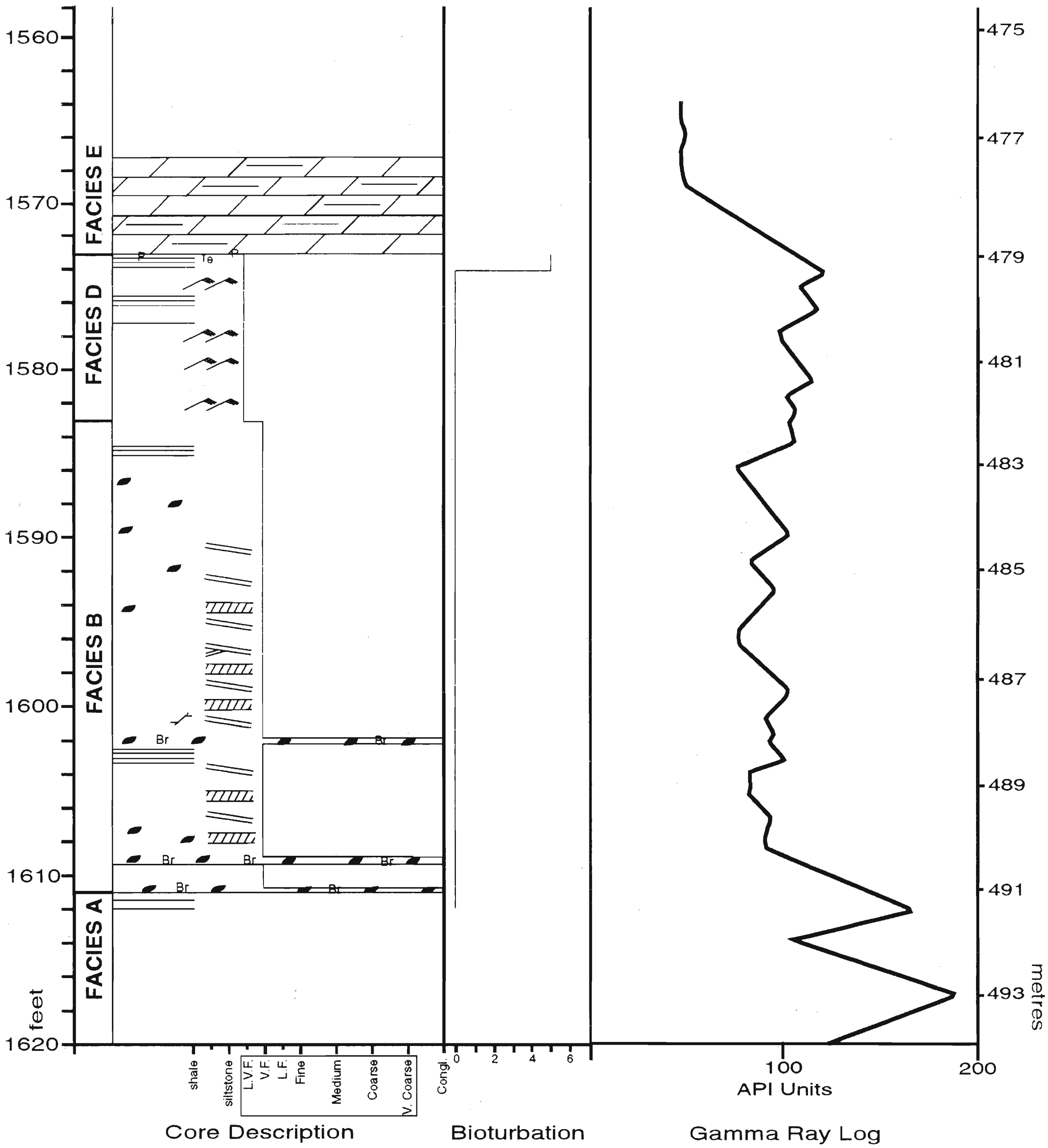


Figure 25: This core, Consumers 13237, Block 123-F, has several lag deposits near the base of Facies B. Each deposit is approximately fifteen centimetres in thickness and is followed by a zone of high angle bedding overlain by lower angled bedding. The section is primarily sandstone with very little shale and no facies C is present. Note the massive sandstone with no discernible bedding near the boundary between facies B and facies D in this example.

FACIES C

This facies consists of interbedded, very fine to fine grained, subrounded to subangular, moderately sorted, quartz arenites with sandy shale beds and partings (Figure 26) and tends to have more sandstones than shales. It is generally red to dark red in colour but rarely mottled light gray. Towards its upper boundary, the colour changes from predominantly red to light gray and/or gray-green. The sandstones are commonly argillaceous with abundant shale partings. The boundaries of the interbedded sandstones and shales are normally sharp but can be gradational.

Facies C is commonly located in the middle to upper portions of the Grimsby Formation and occurs in most cores. Its thickness is normally three to seven metres but can be up to ten metres (Figure 27a, b). This facies exhibits a wide range of bedding styles normally in a vertical succession from low angle trough cross-stratification on the bottom overlain by horizontal laminations which are in turn overlain by very common rippled cross-stratification (Figure 28). Bioturbation is variable and not common but where it is present is dominated by *Teichichnus*, *Diplocraterion*, and *Planolites* burrows and the intensity is less than 3 using the semiquantitative classification of Droser and Bottjer (1986).

Generally, individual sandstones and shale units are up to one metre thick but can reach several metres. Locally, the facies can be predominantly sandstones with very little shale (Figure 29a, b), or predominantly shale with very little sand (Figures 30a, b). Facies C differs from Facies B as it is generally finer grained with abundant shale partings and beds. Bedding is commonly low angle, small scale trough and rippled cross-stratification in contrast to the generally high angle and low angle cross-stratification of Facies B.

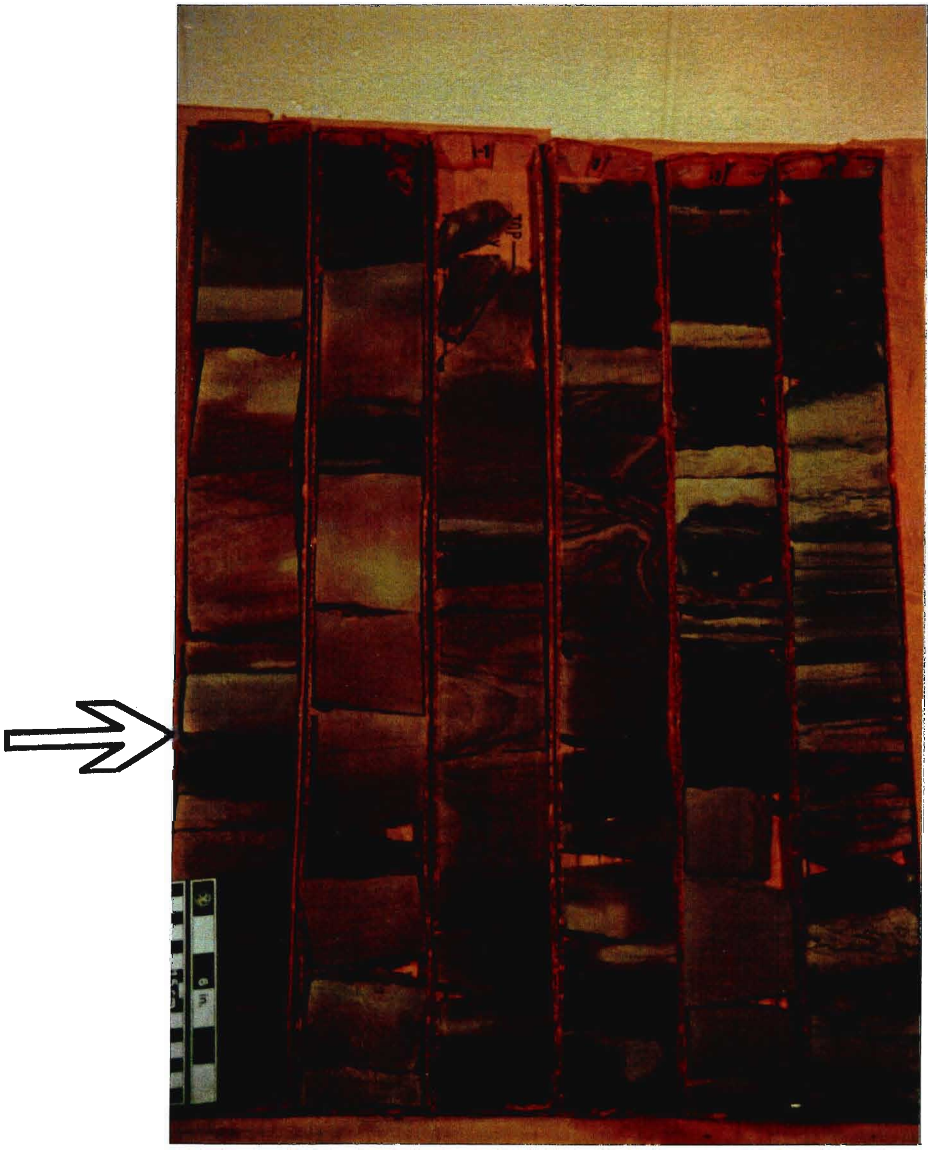


Figure 26: Common appearance of Facies C, in this example (Consumers 13164, Block 157-M), located in the four trays to the left with the lower boundary approximately half way up the far left tray (arrow). The dark red zones are shale partings and beds, the lighter reds are sandstones. The dark red, wavy lines in the two middle trays are diagenetic features. Bedding can be seen as dark gray laminations in the two far left trays. Note the colour change from reds to grays and gray-greens near the upper boundary of the facies located at the top of the second tray from the right. Facies D lies immediately above Facies C in this succession.

Well Name: Pembina #2A Lake Erie 68-Q
Block Number: 68-Q-2A

Latitude: 42 41' 21.98" N
Longitude: 80 33' 36.76" W

Cored Interval: 1247 - 1306 ft.
393.9 - 412.8 m

K.B. Elev.: 616 ft. 187.8 m
Pet. Res. Core No.: #919

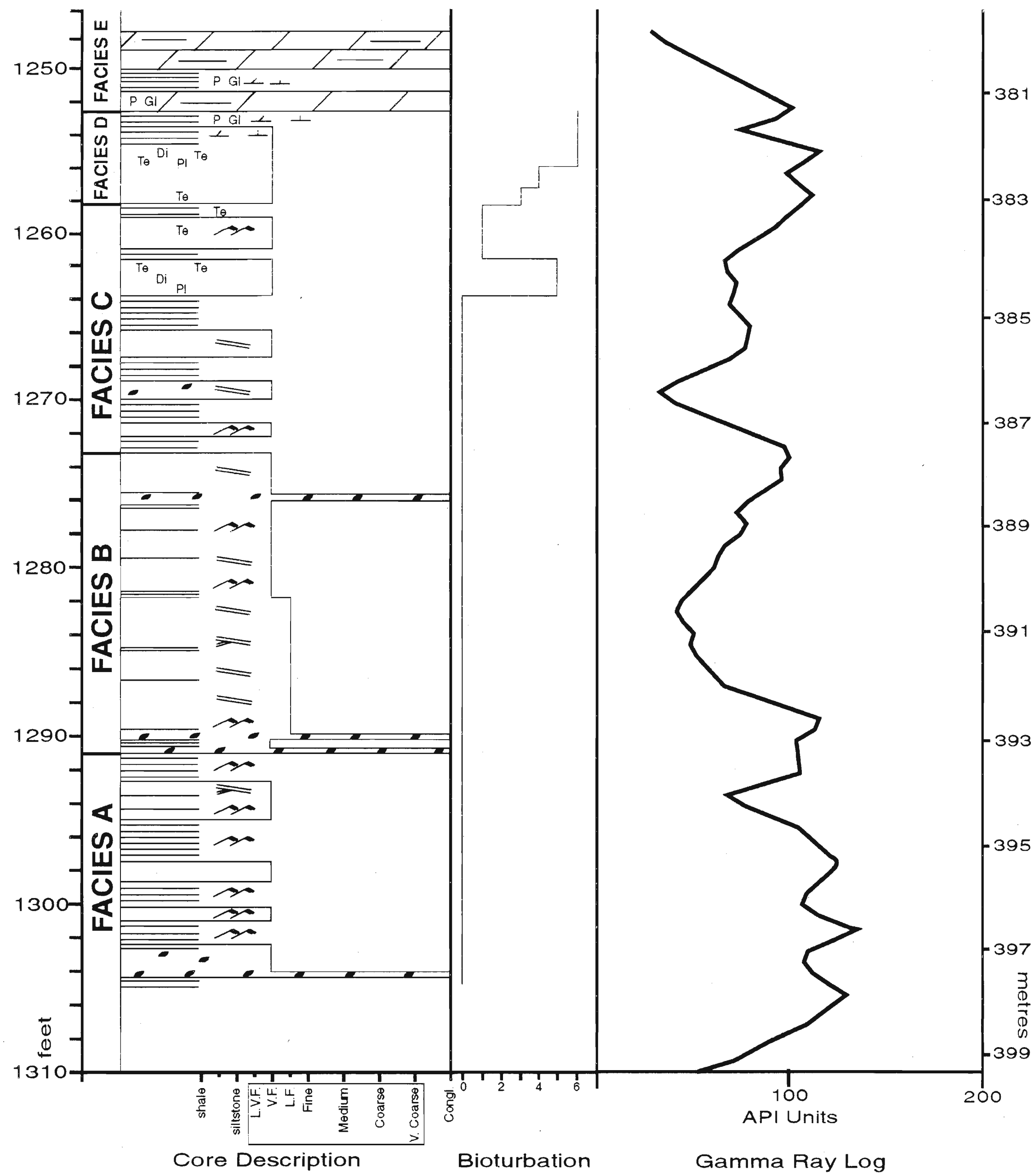


Figure 27a: Pembina #2A, Block 68-Q, illustrating a 'normal' Facies C succession. The facies in this core is approximately five metres in thickness and is bounded below by Facies B and above by Facies D. The distribution of sandstones and shales is common for this facies.

Well Name: Consumers 13167
Block Number: 152-N

Latitude: 42 22' 10.81" N
Longitude: 80 28' 36.21" W

Cored Interval: 1780 - 1830 ft.
542.5 - 557.8 m

K.B. Elev.: 616 ft. 187.8 m
Pet. Res. Core No.: #336

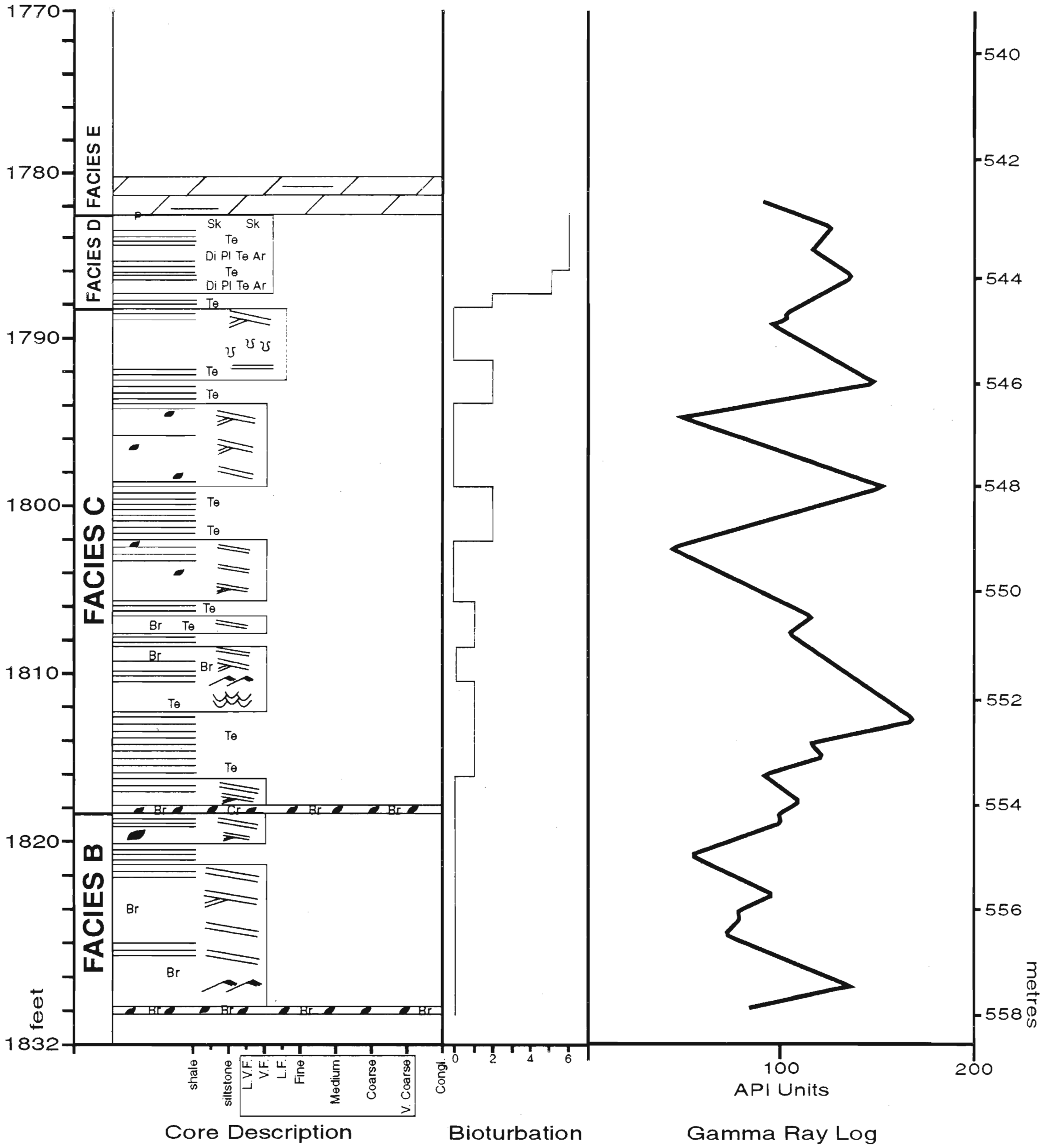


Figure 27b: Consumers 13167, Block 152-N, illustrating an abnormally thick Facies C succession. In this example, Facies C is approximately eleven metres thick. The distribution of sandstones and shales is quite normal for the facies.

Figure 28: Ripple cross-stratification from Facies C, Consumers 13153, Block 122-J. The dark red, curved lines in the upper half of the core are diagenetic features. The gray mottling is common in this facies. Scale is at bottom of core.

Well Name: Consumers 13214
Block Number: 122-L

Latitude: 42 27' 15.63" N
Longitude: 80 41' 17.23" W

Cored Interval: 1610 - 1666.6 ft.
490.7 - 508.0 m

K.B. Elev.: 617 ft. 188.1 m
Pet. Res. Core No.: #188

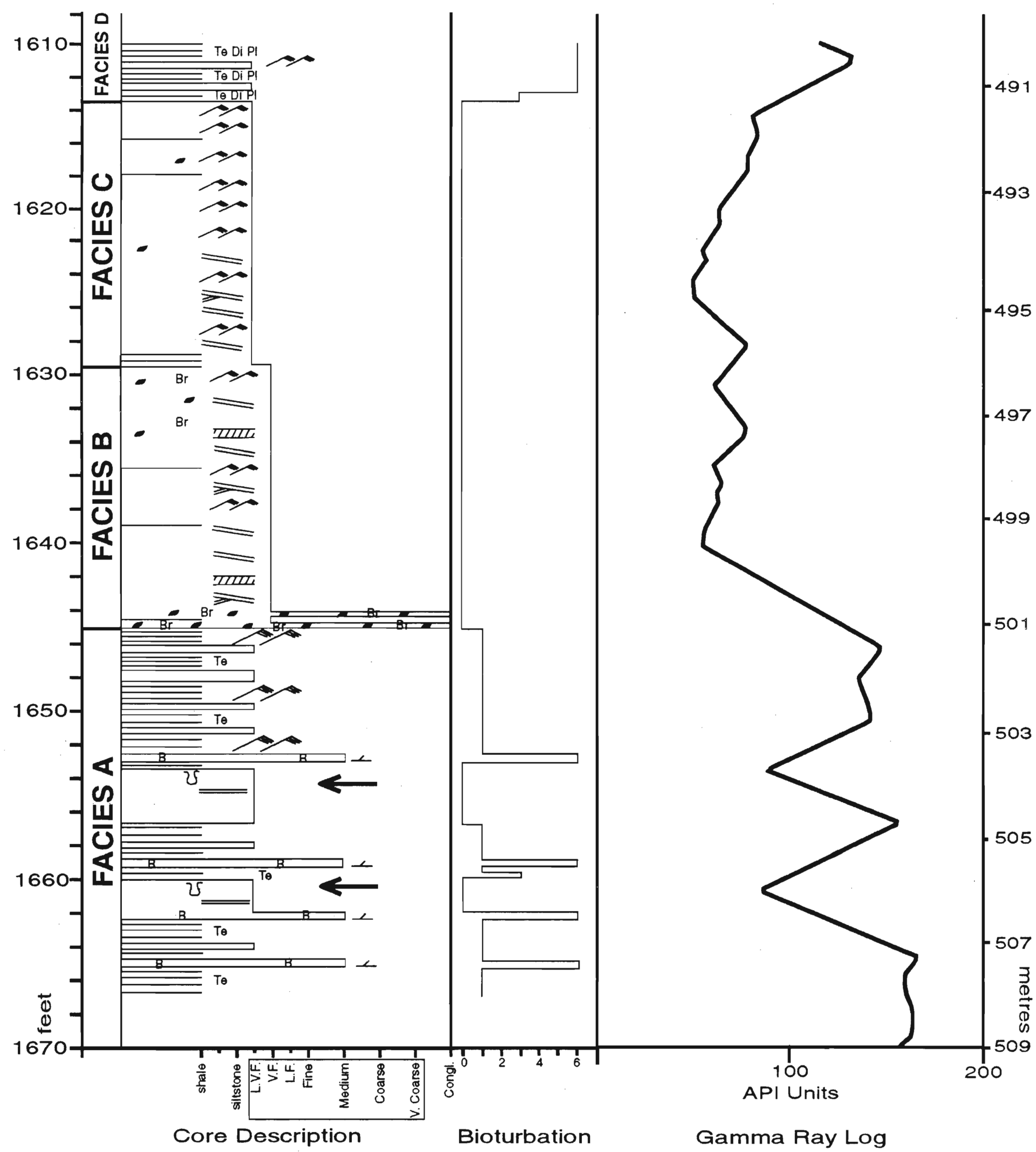


Figure 29a: Consumers 13214, Block 122-L, illustrating a sandstone dominated Facies C. Arrows indicate the dish structured sandstones of Facies A.

Well Name: Consumers 13232
Block Number: 155-W

Latitude: 42 20' 20.01" N
Longitude: 80 42' 18.58" W

Cored Interval: 1830 - 1888.5 ft.
557.8 - 575.6 m

K.B. Elev.: 617 ft. 188.1 m
Pet. Res. Core No.: #405

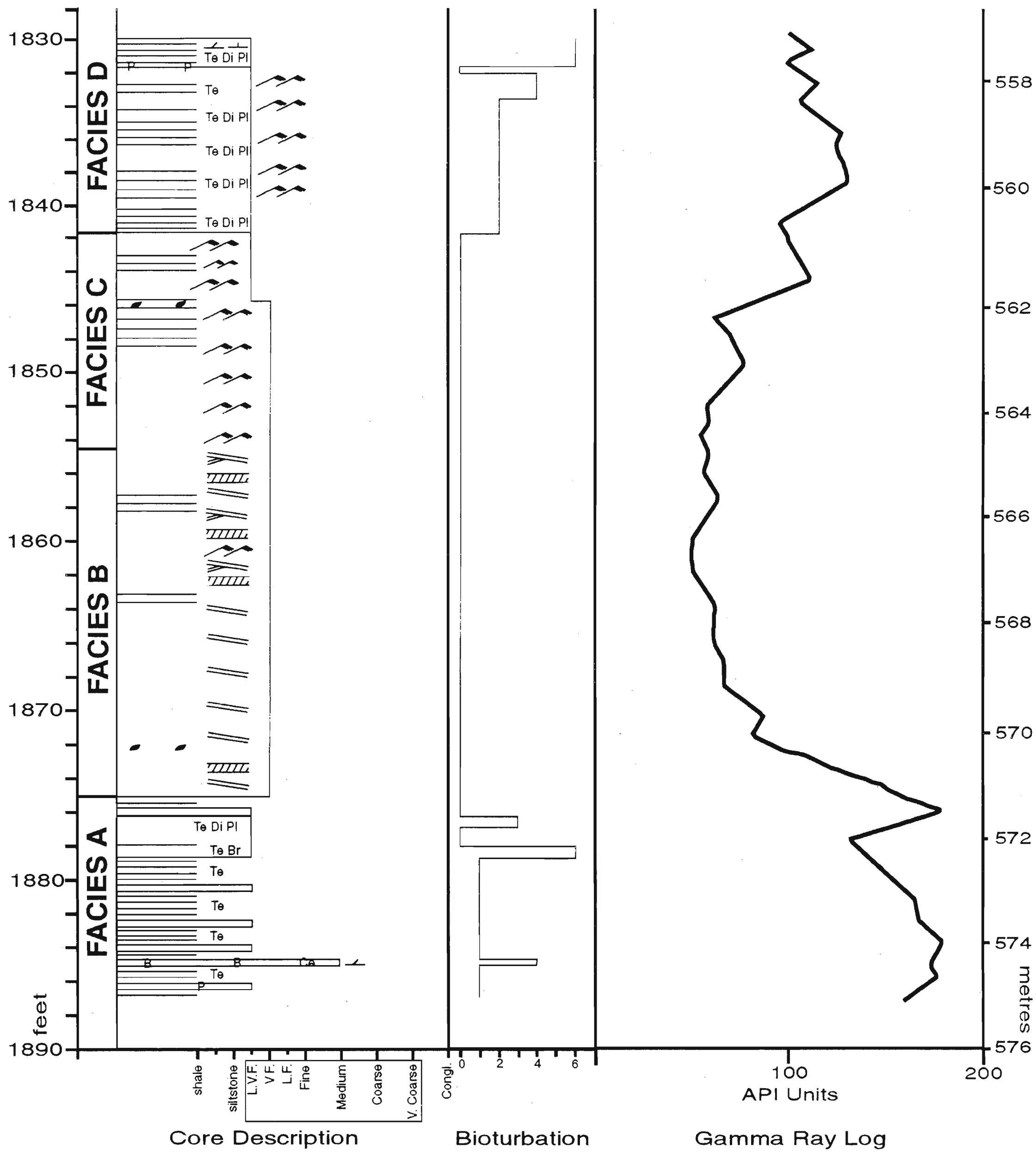


Figure 29b: Consumers 13232, Block 155-W, illustrating a sandstone dominated Facies C.

Well Name: Consumers 13228
Block Number: 122-T

Latitude: 42 26' 34.63" N
Longitude: 80 40' 29.07" W

Cored Interval: 1630 - 1676.5 ft.
496.8 - 511.0 m

K.B. Elev.: 619 ft. 188.7 m
Pet. Res. Core No.: #313

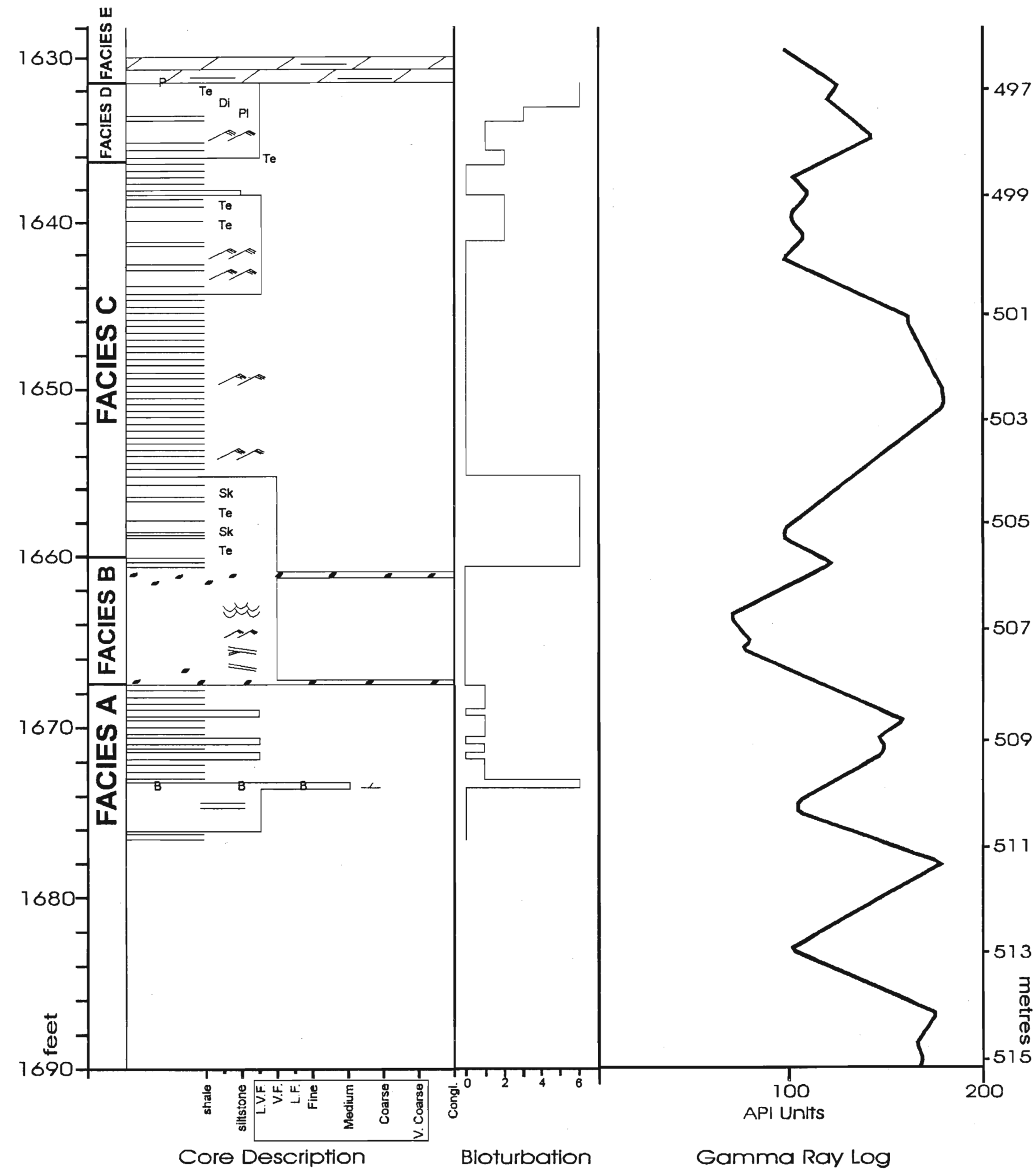


Figure 30a: Consumers 13228, Block 122-T, illustrating a shale dominated Facies C.

Well Name: Consumers 13094
Block Number: 124-C

Latitude: 42 29' 04.61" N
Longitude: 80 32' 57.50" W

Cored Interval: 1537 - 1597 ft. (1589-97 lost)
468.5 - 486.8 m

K.B. Elev.: 602 ft. 183.5 m
Pet. Res. Core No.: #168

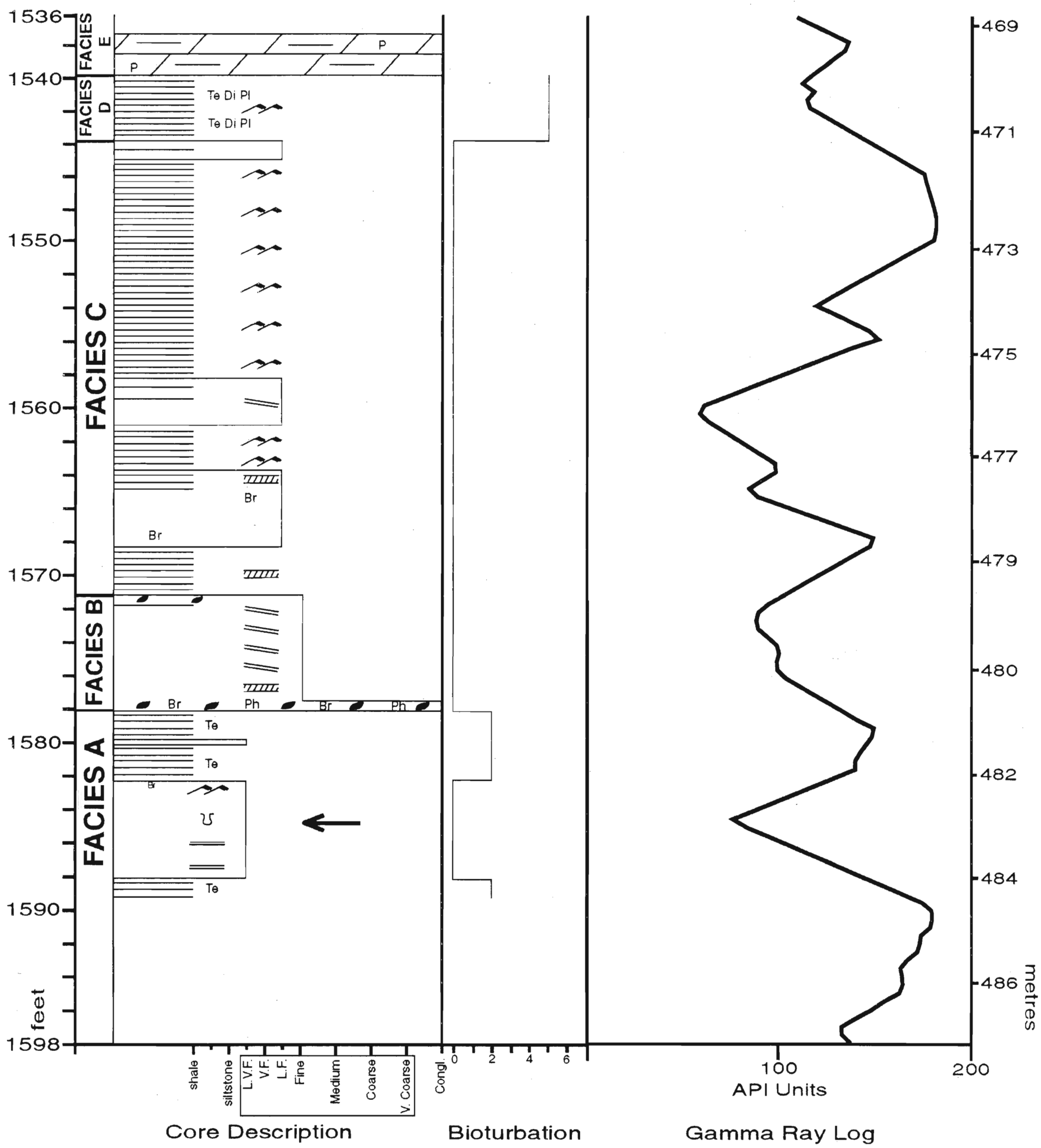


Figure 30b: Consumers 13094, Block 124-C, illustrating a shale dominated Facies C. Arrow indicates dish structured sandstone of Facies A.

FACIES D

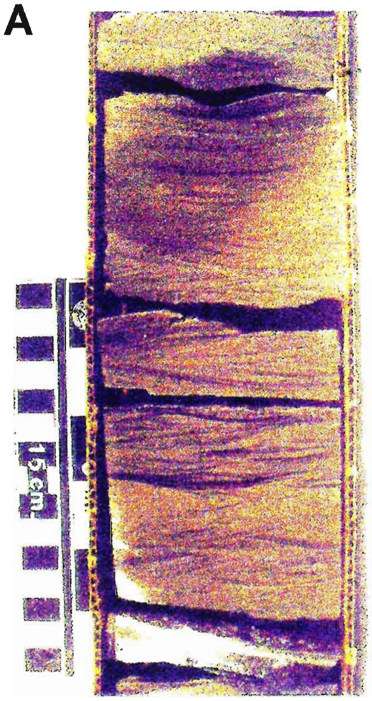
The upper most facies of the Grimsby - Thorold formations, Facies D normally includes all of the Thorold Formation. This facies is likely more than one facies but to sudivide it was beyond the scope of this thesis. It consists of very fine grained quartz arenites with subrounded, moderately sorted grains. The sandstones are largely siliceous but locally are calcareous or dolomitic. The facies is normally very argillaceous with abundant shale partings and beds commonly up to 1 metre thick, although it may locally be all shale or all sandstone, hence the possibility that Facies D is more than one facies. The sandstones are normally light gray to white, and the shales can be gray to gray-green (Figure 26, 27a, 31).

The sandstones in Facies D commonly display rippled cross-laminations and less commonly horizontal lamination (Figure 32a, b, c). High and low angle cross-bedding which are common in Facies B and C are rarely observed in Facies D. The facies is also commonly highly bioturbated, in some cases completely reworking the facies leaving no discernible bedding. Bioturbation is up to level 6 on the semiquantitative scale of Droser and Bottjer (1986). *Teichichnus*, *Diplocraterion* and *Planolites* are the most common trace fossils while *Skolithos* burrows are preserved locally (Figure 33a, b; Figure 34).

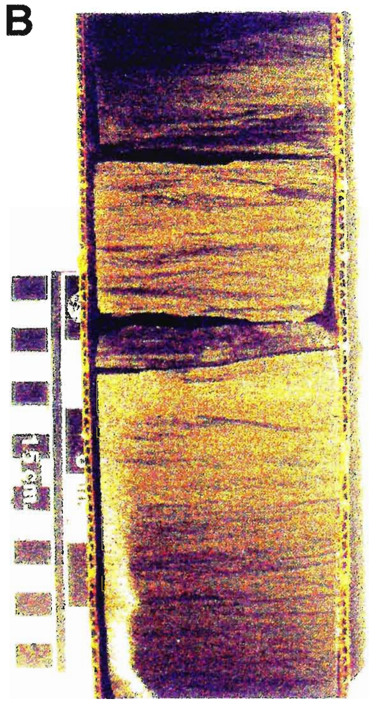
The lower boundary for Facies D is gradational and was problematic. It was placed based upon the commonly higher intensity of bioturbation, the finer grain size, the rippled cross-laminae, and the generally more argillaceous lithology that occurs within this facies in comparison to Facies C. However, this coarsening does not always occur (Figure 32b) so gamma ray curves were utilized to discern a boundary. In Figure 32b, the gamma ray curve deflects to the left which indicates a slight coarsening. The Facies D lower boundary was placed based on the left deflection and, in core, the increase in bioturbation

Figure 31: Facies D, Consumers 13170, Block 94-M. The lower boundary of the facies is approximately where the scale is. The upper boundary with Facies E is located directly above the brown staining in the tray to the far right. This example has good bioturbation throughout the facies and some rippled cross-laminations (middle of second tray from the right). The scale is 15 cm long and located at the bottom of the core and the top of the core is in the far upper right corner.

A



B



C

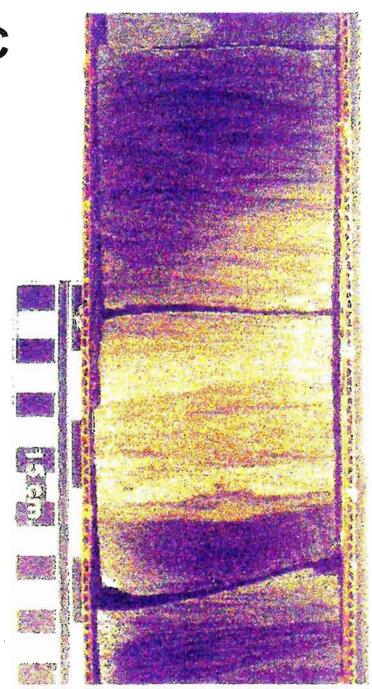


Figure 32a, b, c: Three examples of a sequence of rippled cross-stratification in Facies D, Consumers 13167, Block 152-N. Scale is at bottom of each core.

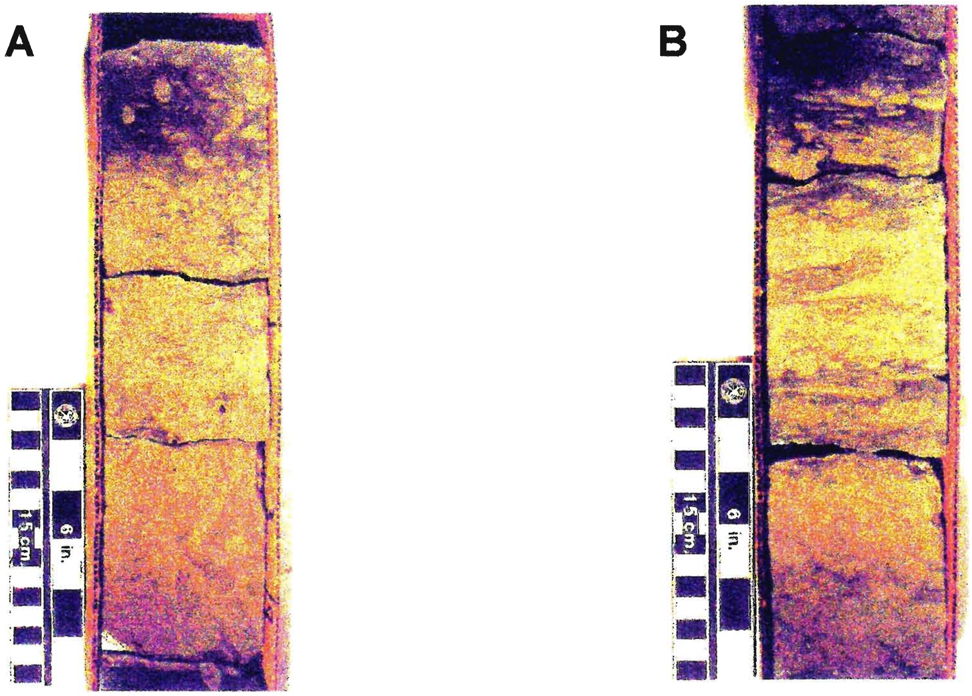


Figure 33a, b: Heavily bioturbated Facies D from Consumers' 13197, Block 153-H. *Teichichnus, Diplocraterion,* and *Planolites* are the most common ichnofossils. Scale is at bottom of each core.

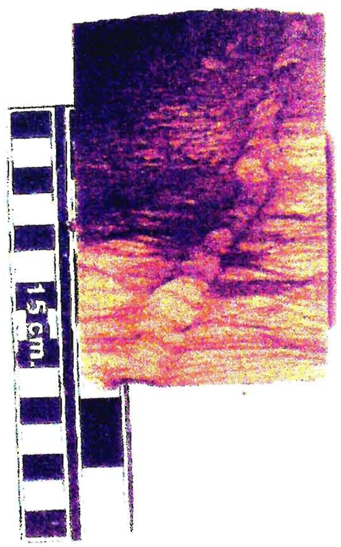


Figure 34: *Teichichnus* burrow in Facies D from Consumers 13170, Block 94-M. Scale is at bottom of core.

intensity. The upper boundary is normally very sharp and commonly marked by a zone of disseminated and nodular pyrite, and phosphate pebbles (Figure 35). This zone is ordinarily fifteen to twenty centimetres thick and, in some cases, is the zone of most intense bioturbation.

FACIES E

Facies E is confined to the Reynales Formation and is predominantly a gray-buff, argillaceous, microsucrosic dolomite (Figure 35) with occasional shale partings. The facies is locally sandy and slightly calcareous with common, small phosphate nodules, and disseminated and small nodular pyrite near it's base along with traces of glauconite. In many cases, coring was begun after drilling through the Reynales Formation and this facies is not present in the recovered core. If present in the core, the facies occurs at the top of each core section and is easily identifiable by the change in lithology from siliciclastics to carbonates.

FACIES IDENTIFICATION IN WELL LOGS

Figures 36 through 40 illustrate the facies as they commonly appear in well logs. The gamma ray well log curve of Facies A indicates that the facies is primarily a shale with minor sandstones. The curve is quite regular from well to well over much of the study area but the sandstones are generally uncorrelatable as they are too thin to be adequately identified. Towards the eastern end of Lake Erie, the facies is noticeably sandier in well logs with a thick (five to seven metres), unnamed sand below any cored intervals. The sand appears to be sharp based and fines upwards into shales. The upper, dish structured sandstone body, described in Facies A, has a distinctive, sharp deflection to the left in the

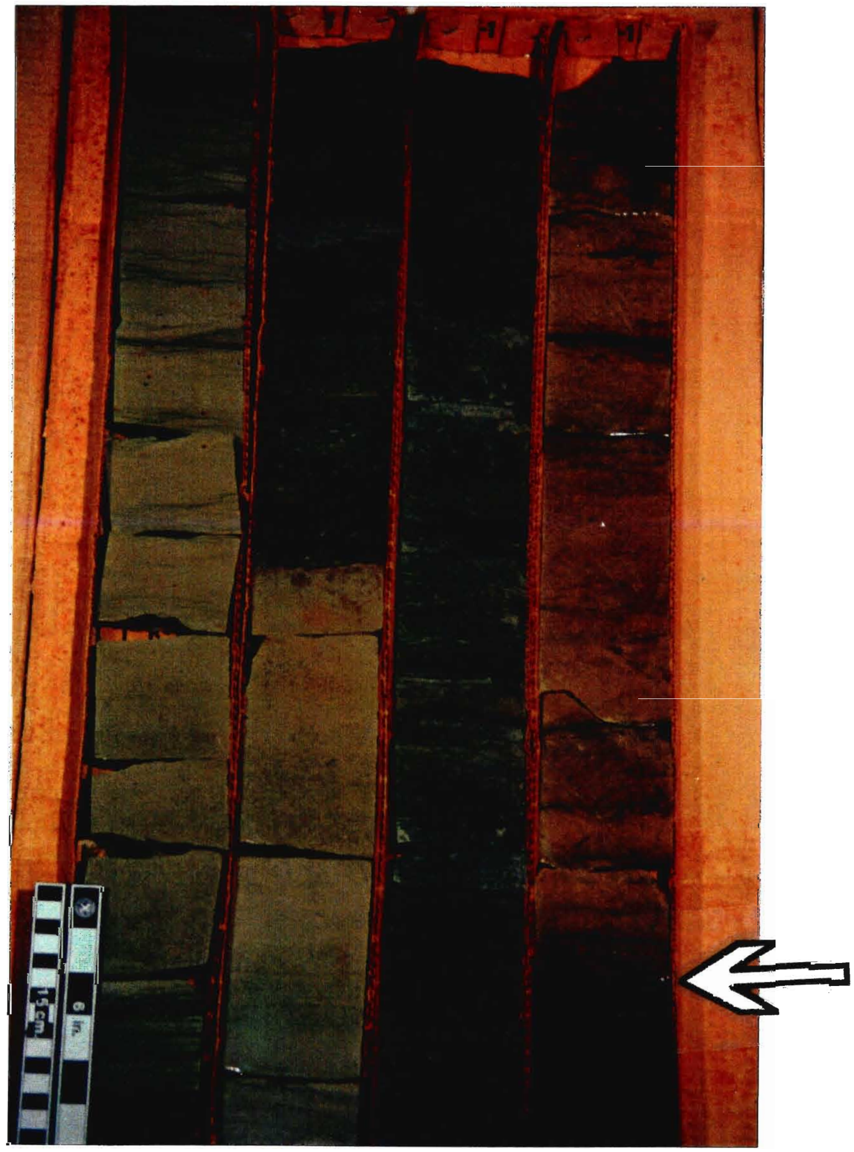


Figure 35: Boundary between Facies D and Facies E. The boundary is indicated by the arrow. The dark gray, heavily bioturbated, very argillaceous sandstone can be considered part of Facies D. The dolostone of Facies E (Reynales Formation) is the light brown core of the far right tray. Scale is 15 cm long and located at the bottom of the core and the top of the core is in the far upper right corner.

CONSUMERS 13202, BLOCK 155-F

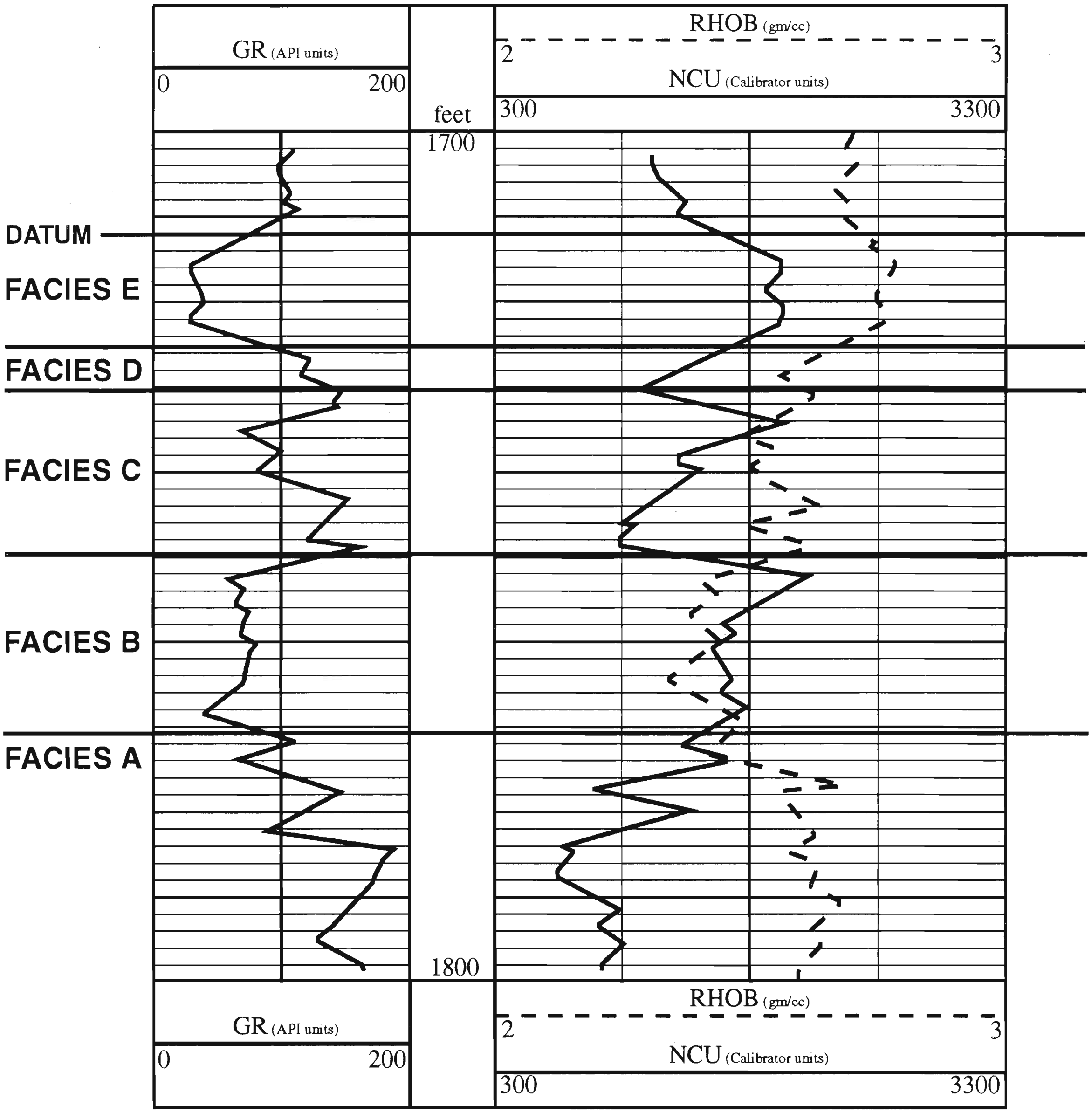


Figure 36: Common well log appearance for facies in Consumers 13202, Block 155-F. This suite of logs includes the Gamma Ray in API units, the Neutron Calibrator log (NCU) in counts, and the Bulk Density log (RHOB) in gm/cc. Facies B fines upwards, Facies C is composed of sandstones and shales with a shale base, and Facies D is primarily shale with a very fine grained sandstone at its upper boundary with Facies E. This well is a gas producer in the Clear Creek Field and its producing zone is in Facies B.

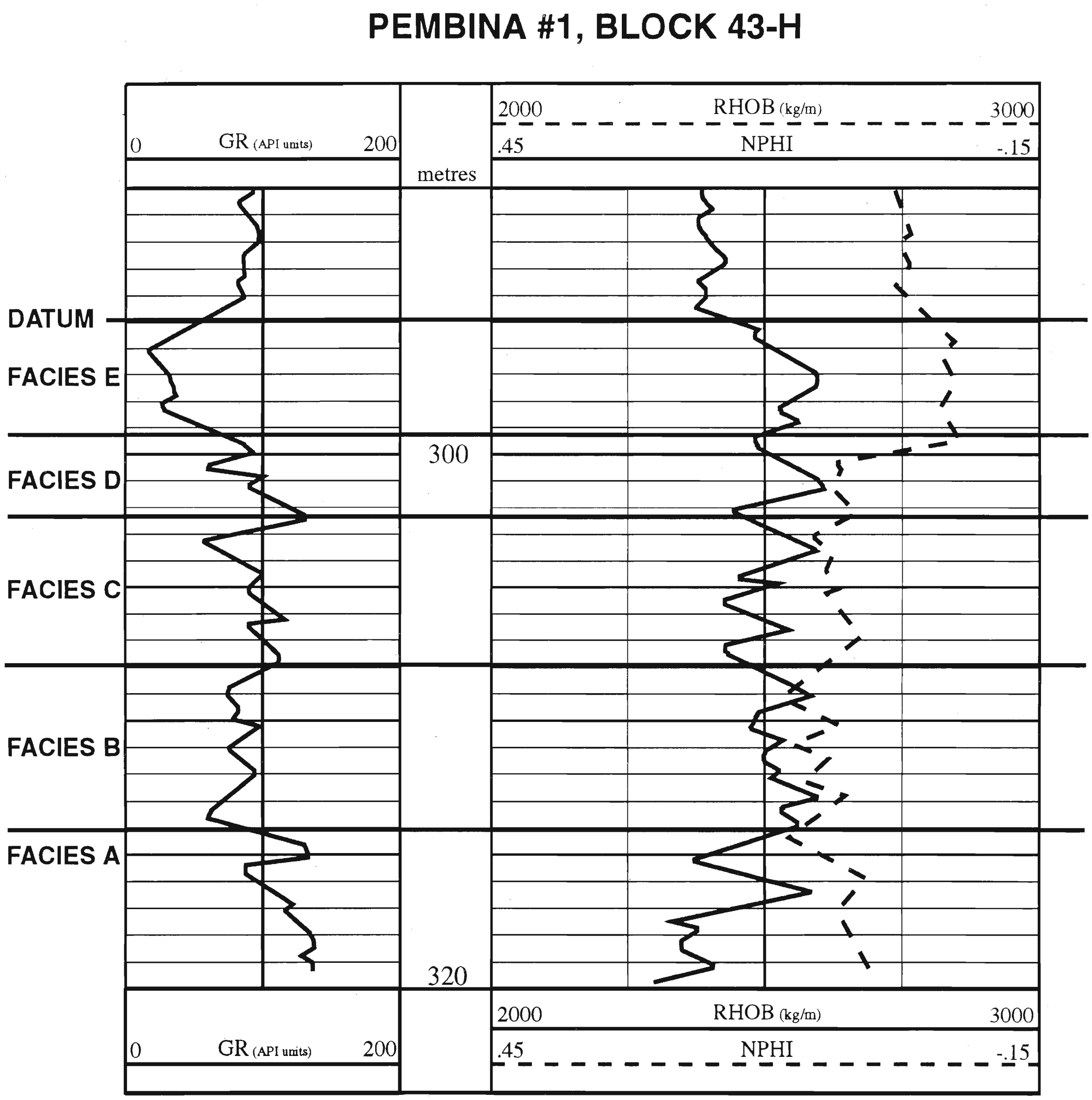


Figure 37: Well log appearance for facies, Pembina #1 Lake Erie, Block 43-H, in the eastern half of the lake. Facies B is a fining upwards facies with minor shales, Facies C is interbedded sandstones and shales, and Facies D is slightly coarser grained with a very fine to fine grained sandstone and a shale at its upper boundary with Facies E. Facies B exhibits a sharp gamma ray deflection to the left common to the facies. The well had a small gas show but was later abandoned.

CONSUMERS 13223, BLOCK 154-G

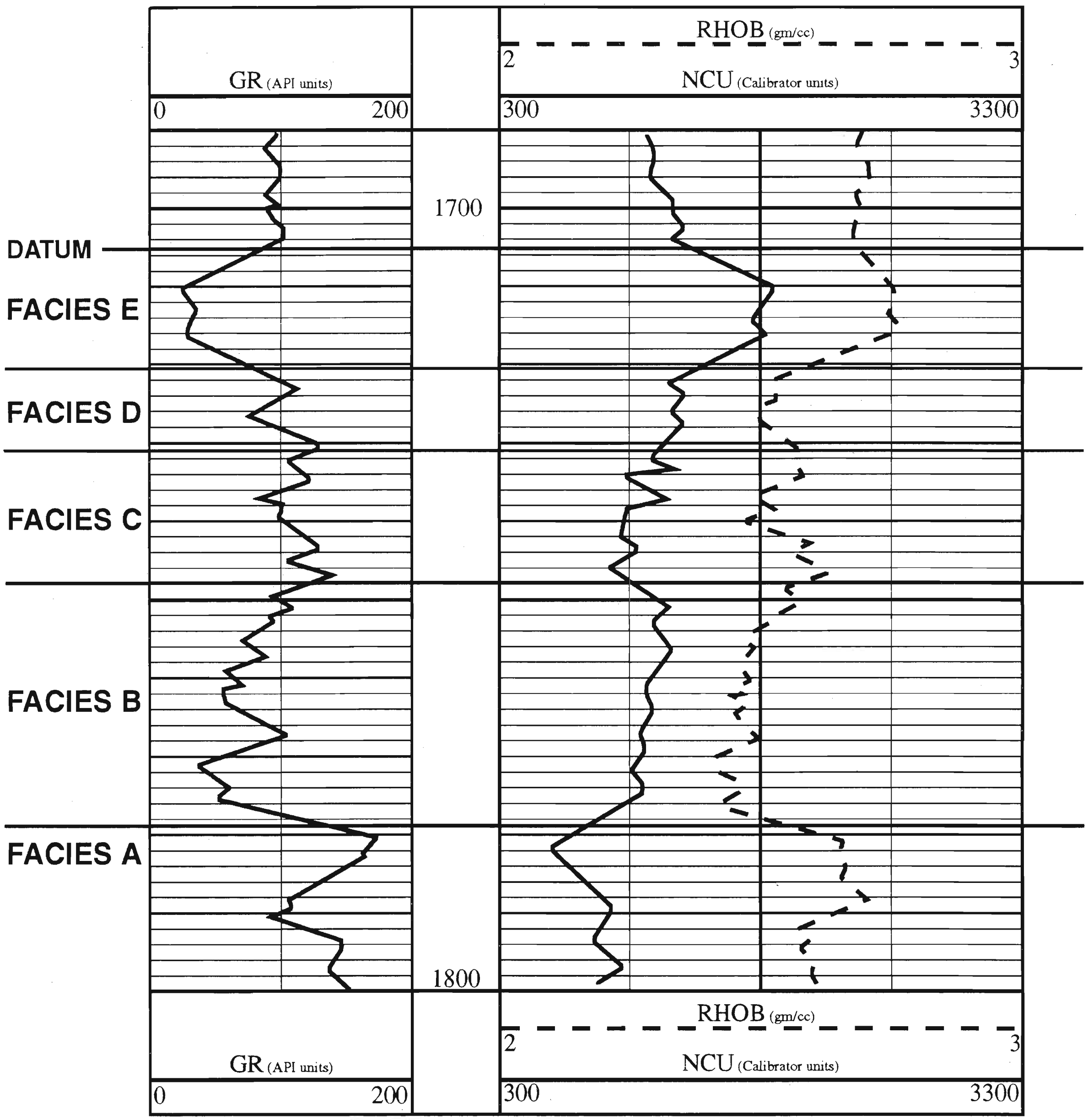


Figure 38: Well log appearance for facies, Consumers 13223, Block 154-G, located within the Clear Creek field. Facies B fines upwards and Facies C is interbedded thin sandstones and shales. A slight coarsening occurs in Facies D. Note that the Neutron Calibrator curve (NCU) and the Bulk Density curve generally track each other and there is no crossover. The well was dry and abandoned.

gamma ray log, and is correlatable between wells (Figure 42). The density curve varies little through the facies.

Facies B in well logs exhibits a sharp deflection to the left on the gamma ray log, indicating a well developed, clean sandstone with little shale. The curve gradually shifts to the right upwards indicating an increase in finer grained sandstones and argillaceous sediments. The density porosity curve deflects sharply to the left indicating a drop in the overall density of the rock and the neutron density curve sharply deflects to the right indicating increasing porosity. The two curves commonly give the gas crossover effect. This facies appears very similar in well logs from well to well.

Facies C is the most variable of the facies and is also the most variable of the facies in well logs. The gamma ray curve reflects this lithologic variability by its 'ragged' appearance, that is, it gives extreme readings from left to right that suggest interbedded shales and sandstones and variable grain sizes. The overall trend of the facies is commonly fining upwards with the gamma ray curve, suggesting more shale in the upper half of the facies. The density and neutron porosity curves are similar to those of Facies B and indicate interbedded sandstone and shale. The gas effect crossover in sandstones is less common.

In the eastern portions of the study area, many well logs of Facies C display a common shale layer, normally located in the upper half of the facies, which commonly forms the boundary between Facies C and D. Its thickness varies from one or two metres to four or five metres. Correlation is difficult as it also varies in vertical location from well to well. The shale layer tends to disappear in the central portion of the study area.

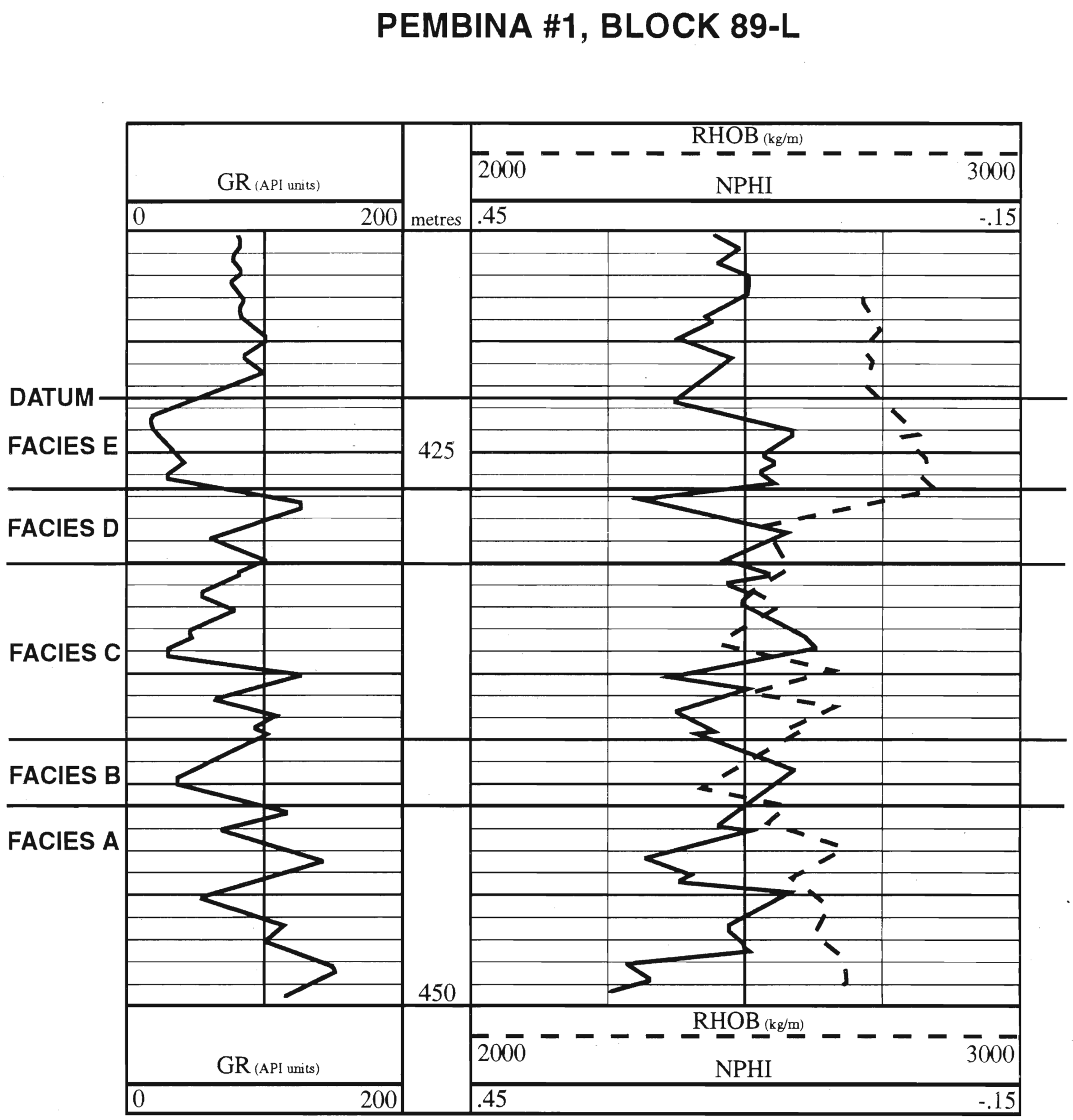


Figure 39: Well log appearance for facies, Pembina #1 Lake Erie, Block 89-L. In this well, both Facies B and Facies C fine upwards but Facies C is generally shalier. Facies D has a sandstone at its base with a shale at the boundary with Facies E. Several crossovers occur with the intervals being the gas producing zones in this gas well within the Maitland field.

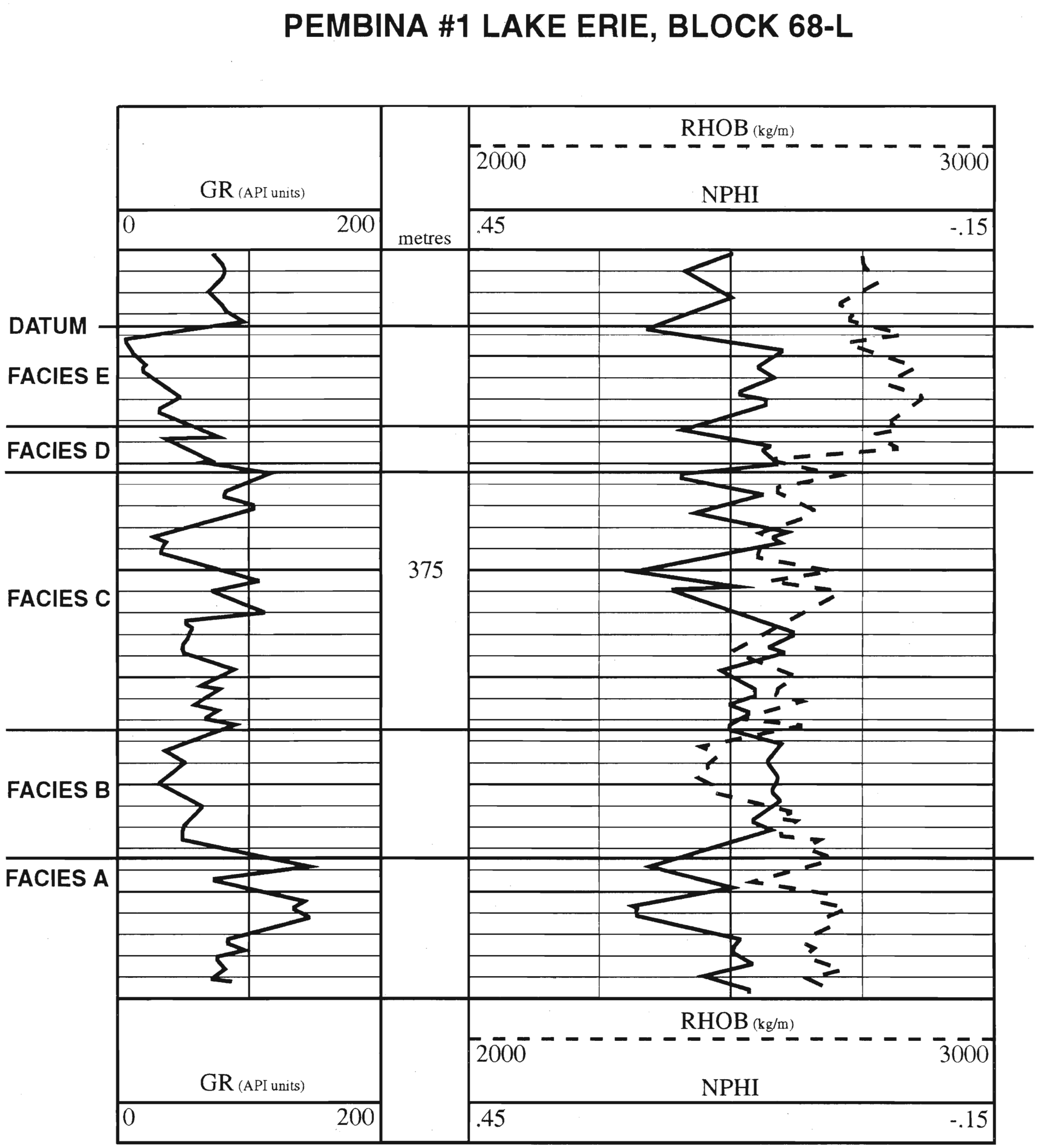


Figure 40: Well log appearance for facies, Pembina #1 Lake Erie, Block 68-L. In this well, Facies B is the coarsest of the facies. Facies C is generally a sandstone with shales. Facies C has two generally fining upwards sequences and is mainly sandstone with lesser thicknesses of shale. The boundary area with Facies D is dominated by shale for several metres. Facies D is only about one metre thick and coarsens from Facies C with a sandstone. This well is a gas producer within the Maitland field from an interval within Facies B.

Facies D is also quite variable in well logs. Normally, the gamma ray curve deflects slightly to the left indicating it is slightly coarser grained than the underlying Facies C. The lower facies boundary was commonly placed at this position. However, the slight coarsening may not be present as the facies can be very argillaceous, deflecting the gamma ray curve to the far right, indicating shales. The lower boundary would be placed at that position. The neutron porosity and density curves rarely have a gas crossover effect within the sandstones. The density of the rock is similar to the underlying facies.

The well log curves for Facies E are quite markedly different from the other four facies because the lithology is a carbonate. The gamma ray curve sharply deflects far to the left, an indicator of a clean carbonate. The neutron porosity curve also sharply deflects to the left, indicating a lack of pore space, and the density curve sharply deflects to the right, indicating an increase in the overall rock density. The deflections are always in tandem at the lower boundary of the facies.

PALYNOLOGICAL OBSERVATIONS

Six samples of shale from the Cabot Head (corresponding to Facies A) and the Grimsby - Thorold formations (corresponding to Facies D) obtained from cores within the study area were submitted for palynological analyses. Table 4 lists the samples, giving the sample number, source core, K.B. elevation and weight used for each sample.

Samples WGP1, WGP3 and WGP4 contained few or no identifiable palynomorphs (Parkins, 1994). Samples WGP2, WGP7 and WGP8, however, contained palynomorphs that were sufficiently abundant and well preserved to merit detailed examination. Preservation ranged from poor to excellent, even within the same sample. The palynomorphs have been compressed flat as the host rock is a shale and none were inflated to any degree. Thus no evidence was present to indicate the original shape or degree of inflation. Table 5 presents the results of the analysis of samples WGP2, WGP7 and WGP8.

The three samples, WGP2, WGP7 and WGP8, were dominated by simple, round, possibly sperical palynomorphs with thin walls which were variously wrinkled and/or folded (Parkins, 1994). They ranged in diameter from 15 to 80 microns. These could have been either sphaeromorph acritarchs or simple spore-like palynomorphs. It is not possible to determine to which group these palynomorphs belonged and it was quite likely that both groups were represented in these assemblages.

Sample WGP8 contained the greatest diversity of palynomorphs (Parkins, 1994). Both acritarchs and a variety of spore-like palynomorphs were present. Sample WGP7 contained spore-like palynomorphs and only a single fragment which might have belonged to an acritarch. Sample WGP2 consisted of spore-like palynomorphs and no acritarchs were found.

SAMPLE NUMBER	SOURCE CORE AND LOCATION	K.B. DEPTH		WEIGHT USED
		(ft)	(m)	(gm)
WGP1	Consumers 13228, Block 122-T	1632.9	497.7	4.63
WGP2	Consumers 13223, Block 154-G	1727.0	526.4	5.99
WGP3	Consumers 13171, Block 185-C	1875.7	571.7	5.52
WGP4	Consumers 13273, Block 158-K	1770.7	539.7	6.58
WGP7	Consumers 13228, Block 122-T	1648.9	502.6	3.28
WGP8	Consumers 13214, Block 122-L	1665.0	507.5	3.68

Table 4: Summary of samples submitted for palynological analyses.

SAMPLE NUMBER	ACRITARCHS	SPORE-LIKE PALYNOMORPHS	MISC.
WGP8 Consumers 13214, Block 122-L	*Cymatioshaera densisepta* Miller and Eames 1982 (one specimen) *Diexallophasis remota* (Deunff) Playford 1977 (14 specimens) *Disparifusa psakadoria* Loeblich and Tappan 1978 (three specimens) *Eupoikilofusa* cf.*E.striata* (Stablin, Jansonius and Pocock) Loeblich and Tappan 1978 (five specimens) *Eupoikilofusa rhomba* Miller and Eames 1982 (fragment of one specimen) *Leiofusa* species (two specimens) *Leiosphaeridia* species B of Miller and Eames 1982 (one specimen) *Micrhystridium ? polorum* Miller and Eames 1982 (two specimens) *Micrhystridium* species (four specimens) *Multiplicisphaeridium* species A of Miller and Eames 1982 (one specimen) *Multiplicisphaeridium* species C of Miller and Eames 1982 (one specimen) *Veryhachium europaeum* Stockmans and Williere 1960 (22 specimens) *Veryhachium lairdi* (Deflandre) ex Deunff 1959 (three specimens) *Veryhachium trispinosum* (Eisenack) Deunff ex Downie 1959 (five specimens) *Veryhachium* species (one specimen) Unidentified acritarchs (two specimens)	*Dyadospora murusattenuata* Strother and Traverse 1979 (one specimen) *Nodospora burnhamensis* Strother and Traverse 1979 (two specimens) *Tetrahedraletes medinensis* Strother and Traverse 1979 (three specimens) *Vermiculatisphaera obscura* Miller and Eames 1982 (three specimens) Mother cell enclosing four daughter cells as in Strother and Traverse 1979, pl. 3, Fig. 8 (one specimen)	Cell clusters: -2 cells (one specimen) -3 large cells (one specimen) -4 cells (one specimen)
WGP7 Consumers 13228, Block 122-T	Fragment with reticulate ornament (one specimen) possibly *Moyeria cabotti* (Cramer) Miller and Eames 1982 or *Eupoikilofusa ? rhomba* Miller and Eames 1982 or something else entirely	*Nodospora burnhamensis* Strother and Traverse 1979 (six specimens plus one tetrad) *Nodospora* ? new species (one specimen) *Rugosphaera ? cerebra* Miller and Eames 1982 (two specimens) *Rugosphaera tuscarorensis* Strother and Traverse 1979 (one specimen) Unidentified tetrad (one specimen)	Cell clusters: -3 cells (two specimens) Tubes: -smooth surface (four specimens) -with reticulate network (two specimens) -with longitudinal fibers (four specimens)
WGP2 Consumers 13223, Block 154-G	None observed	*Dyadospora murusdensa* Strother and Traverse 1979 (one specimen) *Dyadospora murusattentuata* Strother and Traverse 1979 (one specimen) *Tetrahedraletes medinensis* Strother and Traverse 1979 (three specimens)	Cell Clusters: -3 cells (three specimens, one with large cells) -4 cells (two specimens) -5 cells (one specimen) -6 cells (one specimen) -13 cells (one specimen)

Table 5: Summary of identified palynomorphs from samples WGP8, WGP7 and WGP2 (Parkins, 1994).

INTERPRETATION OF OBSERVATIONS

FACIES INTERPRETATIONS

Based on the observations and identification of facies from cores and well logs, an interpretation of the paleoenvironment of each facies can be made. Table 6 summarizes the observations and interpretations for the facies.

FACIES A

Facies A is composed of interbedded shale with thin beds of very fine grained sandstone and a thicker sandstone present near the upper boundary of the facies. The thin sandstone beds have sharp bases with the shales and, in many cases, have a basal lag of fossil fragments. They are also somewhat argillaceous, have wavy to horizontal laminations and are laterally not very extensive, as they are virtually uncorrelatable from well to well, except in one case. In this one case, the thick sandstone body of the Upper Cabot Head Formation, hummocky cross-stratification (HCS) is common. HCS is normally found in very fine to fine-grained sand, similar to that of the sandstone body, with the frequency of its occurrence decreasing with increasing grain size (Cheel and Leckie, 1993). HCS is common in sandstones that are interpreted as the deposits of storm-surges and have been well documented as a common feature of storm deposits (Duke, 1985; Duke, 1990; Duke *et al.*, 1991a). The dish structures which are also common to this sandstone are of little value in determining the paleoenvironment having been found in many depositional settings (e.g. Rautman and Dott, 1977; Wentworth, 1967) but do indicate that their associated sediments were deposited rapidly, trapping interstitial pore water (Wentworth, 1967). Lowe (1975) documented dish structures in sequences made up of alternating fine- (clay and mud) and coarse-grained (sand) units similar to Facies A.

The sandstones of Facies A are interpreted as storm deposits that were laid down on a broad, shallow shelf that received only mud during normal, fairweather conditions. The thicker sandstone with HCS and dish structures which is correlatable over much of the study area is possibly an amalgamated storm bed. In some wells, this thick sandstone is replaced by two separate sandstones with a shale between them. Near the northern limits of the study area, the sandstone body becomes finer grained and consists of a series of interbedded sandstones and shales.

The fossiliferous, bryozoan-rich, dolomitic sandstones that are common in this facies are also not correlatable from well to well. The bryozoans within these beds are lying horizontally and never found in living position (i.e., vertically). They are also normally just fragments with few longer than 2 to 3 cm. Bryozoans optimally live in open, normal marine environments (Boardman and Cheetham, 1987). As well, other fossil fragments associated with these beds such as crinoid fragments are only found in marine conditions (Boardman and Cheetham, 1987). The grain size variations (from very fine to coarse) along with the fragmentary nature of the fossils suggests that these beds are storm deposits where fossil debris and coarser grained sediment was swept in. The presence of fossil fragments at the base of some of the thin sandstones described previously and attributed to storm surges also suggests this.

Teichichnus, a common trace fossil of the softground *Cruziana* ichnofacies, is associated with moderate energy levels in shallow marine waters below fair weather wave base but above storm wave base (Pemberton *et al.*, 1992). The *Cruziana* ichnofacies reflects a lower energy environment dominated by horizontal, deposit feeding organisms

(Frey and Pemberton, 1984). The low diversity of trace fossils suggests a stressed environment which may be caused by variations in temperature, salinity, energy levels, and sediment input (Ekdale *et al.*, 1984).

Sample WGP8, obtained from Facies A, provided the greatest diversity of palynomorphs with both acritarchs and a variety of spore-like palynomorphs present (Parkins, 1994). The acritarchs are indicative of a marine environment. The spore-like palynomorphs are problematic. Both Strother and Traverse (1979) and Miller and Eames (1982) suggested that these were derived from 'pre-vascular' terrestial or semi-aquatic plants. However, both studies carefully point out that until these palynomorphs have been found in the sporangia or conceptacles of plant macrofossils, preferably of Early or Middle Silurian age, that no definitive proof of their origin in terrestial or freshwater environments exists and one can only state with caution that the environment was probably or possibly terrestial or freshwater. The assemblage contained in this sample very closely matches that from sample PGN 11 in Miller and Eames (1982) which was collected from the top of the Power Glen Formation (Cabot Head Formation) at Lewiston, New York.

Because acritarchs indicate a marine environment and the spore-like palynomorphs possible terrestial-freshwater environments and since sample WGP8 from Facies A contained both types of microfossils, this interval was deposited in a nearshore marine environment. The relatively low diversity of the acritarch assemblage would also suggest a marginal environment for these organisms such as one with lower salinity. Spore-like palynomorphs, possibly of terrestrial origin, drifted in from a nearby landmass and were deposited in the shallow marine muds.

The probable paleoenvironment for Facies A is interpreted as a shallow marine, nearshore, shelf environment that is subjected to periodic storms.

FACIES B

Facies B is preserved as a fining upwards sequence of fine to very fine grained sandstone normally with a basal lag deposit of rip-up mud clasts, *Lingula* fragments and phosphatic pebbles. The sharp lower contact with an associated basal lag deposit is indicative of a channel facies (Rahmani, 1988; Frey and Howard, 1986). The facies is dominated by high angle cross-stratification overlain by low angle cross-stratification and is characteristic of channel deposits where there is a shallowing upwards as the channel infills. The fining upwards trend found within this facies also suggests an infilling of channels. The thickness of the high angle and low angle bedding zones, and the fining upwards succession of Facies B change from well to well which suggests a limited lateral extent of the deposition. High angle cross-stratification with mud couplets and mud drapes deposited on the foreset beds indicate a tidal influence (Nio and Yang, 1990). These are interpreted as subtidal channel deposits with the mud couplets representing the deposition of fine-grained sediments during periods of slackwater over the tidal cycle and characteristic of the subtidal zone (Nio and Yang, 1990; Rahmani, 1988). The mud couplets drape alternating thick and thin sand layers suggesting unequal semi-diurnal tides (Nio and Yang, 1990). The basal lag deposits are created by laterally migrating channels which cut flanking mud deposits creating bluffs or bank scarps which slump into the intertidal channels in angular blocks (Rahmani, 1988). The common presence of *Lingula* within the basal lag deposit, a brachiopod common to a variety of brackish, nearshore environments such as mudflats, further suggests channels laterally migrating and incising into sediments in which the brachiopods lived. The meandering channels are recorded by the presence of several lag deposits in some cores which are commonly overlain by coarser grained, high angled sandstones which fine upwards into finer grained sandstones and shales which results in a 'ragged' or highly variable appearance of some gamma ray well logs. The lack of trace fossils also suggests a stressed, brackish water environment with rapid changes in sedimentation rates similar to meandering, subtidal channels.

The probable paleoenvironment for Facies B is a subtidal channel complex.

FACIES C

This facies is composed of interbedded very fine to fine-grained sandstones and shale. The absence of lag deposits and high angle cross-stratification that were common in Facies B and their replacement with sandstones with low angle to rippled cross-stratification as well as the presence of finer grained sandstones and shales within this facies suggests that Facies C was deposited in a lower energy environment than that of Facies B. The low angled cross-stratified to rippled cross-stratified sandstones are interpreted as the deposits of tidal channels. The common sharp bases of the sandstones and occasional mud drapes along the cross-beds are indicative of a subtidal setting (Rahmani, 1988). Mud drapes represent periods of slackwater deposition of fine-grained sedimentation and are indicative of the subtidal zone.

The muds of Facies C are rarely bioturbated and the presence of a limited number of trace fossils of the *Cruziana* ichnofacies suggests a stressed, nearshore environment. The *Cruziana* ichnofacies reflects a lower energy environment dominated by horizontal, deposit feeding organisms (Frey and Pemberton, 1984) and suggests a slow, steady sedimentation rate. The restricted trace fossil assemblage in muds and clays associated with the *Cruziana* ichnofacies common to a marine environment suggest that the trace makers were feeding in organic rich muds located in a quiet, marine to brackish locale (Ekdale *et al.*, 1984). The sandstones do not contain trace fossils. The common low angled cross-stratification overlain by rippled cross-stratification suggests that the environment experienced a gradual decrease in energy. The upper and lower gradational boundaries of Facies C, along with the variability of the lithology from being sandstone dominated near its base to being shale dominated near its upper boundary, suggests that it is a transitional environment from a higher energy, tidally influenced, marine facies to a lower energy, marine to brackish one with little tidal influence. The large, widespread channels of Facies B have been largely replaced by shallower, subtidal channels associated with lower energy shoreface or mud flat deposits.

Facies C is interpreted as shallow, subtidal channels with associated mudflats.

FACIES D

Facies D is an argillaceous, very fine grained sandstone with numerous shale partings and thin shale beds that are commonly heavily bioturbated or commonly ripple cross-laminated. The lower boundary of the facies is gradational with Facies C and the upper boundary is an disconformity. The facies is just slightly coarser than Facies C and commonly has more sandstones than shales but is highly variable and can locally have more shales than sandstones.

The trace fossils present in this facies (*Teichichnus*, *Diplocraterion*, *Planolites*, *Skolithos*) are associated with the *Skolithos* and *Cruziana* ichnofacies (Pemberton *et al.*, 1992). The *Skolithos* ichnofacies is associated with relatively high energy environments while the *Cruziana* ichnofacies is associated with relatively lower energy environments (Ekdale *et al.*, 1984). The ichnofacies suggest a nearshore environment with abrupt changes from high to low energy.

However, palynological observations suggest that Facies D may have been deposited in a non-marine environment. Both sample WGP7 and WGP2 were obtained from two different cores in the interval identified as Facies D and contained only spore-like palynomorphs with no identifiable acritarchs (Parkins, 1994). It would be difficult to explain how a marine environment would not contain or preserve acritarchs while the spore-like palynomorphs were retained and preserved. Thus, both samples were possibly deposited in a non-marine environment.

The very common rippled cross-laminations suggest a low energy environment dominated by unidirectional currents. Non-marine micropaleontology suggests that the rippled sandstones were deposited in a non-marine environment. This seeming contradictory evidence can be accounted for by the suggestion that the bioturbation of the rippled sediments took place well after deposition of the sands but before they were cemented. Palynological evidence suggests this finding as the samples used for investigation were obtained from non-bioturbated, unoxidized locations. The bioturbated portions of Facies D are associated with marine trace fossil assemblages.

Facies D can be subdivided into several facies. It was deposited in a brackish to freshwater, nearshore environment. Further subdivsion is beyond the scope of this thesis.

FACIES E

Facies E, an argillaceous, rarely sandy, dolostone is bounded below by a disconformity associated with phosphatic pebbles, glauconite, and disseminated pyrite. The boundary is very abrupt, normally from the very fine grained sandstones and shales of Facies D to the dolostones of Facies E. This facies represents the cessation of primarily siliciclastic deposition and the beginning of primarily carbonate deposition in a warm, shallow, stable shelf environment. What little siliciclastic material was introduced into the basin during the deposition of this facies was very fine grained and primarily clays and muds.

FACIES	DESCRIPTION and OBSERVATIONS	INTERPRETATION
FACIES A	-composed primarily of dark gray, fissile shale and secondarily buff, silty to very fine grained sandstones -common horizontal laminae and current rippled cross-laminae -common fossiliferous, calcareous to dolomitic, very fine to coarse grained sandstones in a matrix of clay and hematitic cement -low bioturbation intensity, commonly *Teichichnus* and *Planolites* (*Cruziana* ichnofacies) -both acritarchs and spore-like palynomorphs present	-shallow marine, nearshore, shelf environment that was subjected to periodic storms
FACIES B	-is a fine to medium grained quartz arenite that normally fines upwards -common coarse basal lag of rip-up mud clasts, *Lingula* shell fragments and phosphate pebbles -common large scale trough cross-stratification overlain by low angle cross-stratification -common mud couplets on cross beds -no bioturbation	-subtidal channel complex
FACIES C	-interbedded, very fine to fine grained quartz arenites with sandy shale partings and beds -common small scale trough cross-stratifaction overlain by rippled cross-stratification -variable bioturbation (*Cruziana* ichnofacies) in shales -less common mud couplets	-subtidal channels with associated mudflats
FACIES D	-consists of very fine grained quartz arenites and sandy shales -common rippled cross-laminations -commonly very bioturbated (*Cruziana* and *Skolithos* ichnofacies) -only spore-like palynomorphs present	-brackish to freshwater, nearshore environment
FACIES E	-argillaceous, microsucrosic dolostone with occasional thin shale partings and beds -lower boundary has common phosphate pebbles, occasional glaunconite and common pyrite nodules -dolostone is rarely sandy	-warm, shallow, stable shelf

Table 6: Summary of observations and interpretations of defined facies.

GEOMETRY OF THE GRIMSBY - THOROLD FORMATIONS

Four maps were drawn to determine the geometry and extent of the Grimsby - Thorold formations. As well, a cross-section using wells from the west - central portion of the lake was drawn to illustrate the incision and later deposition of the Grimsby - Thorold formations into the Cabot Head Formation.

Map 1, the Total Queenston - Reynales Isopach, was drawn to establish the total thickness of sediment between the top of the Reynales - Irondequoit formations and the top of the Queenston Formation. It eliminates the structural dip to the south of the rocks and establishes the thickness of sediments between these two boundaries. The map suggests that the thickness of Lower Silurian sediments remains relatively constant throughout the study area. A small amount of thickening occurs primarily to the south and to the southwest with thinning occurring to the north towards the Algonquin Arch. This was not unexpected as other studies suggested similar changes in thickness (Brigham, 1971). However, the map suggests that there are no ravinement surfaces, incisions or channels located at the Queenston Formation - Lower Silurian boundary, a development which was surprising as the boundary is an unconformity.

Map 2, the Total Grimsby - Thorold Isopach, establishes the boundaries and total thickness of the Grimsby - Thorold formations. The map suggests that the Grimsby - Thorold formations thicken to the south with the thickest portion along the international border and presumably thickening into the United States. In the western part of the lake, the subcrop limit is in the northwestern part of the study area with the edge then turning to the southwest in the west central part of Lake Erie. In the central and eastern half of the lake, the subcrop limit is beyond the study area. The contours illustrate the two formations are aligned in a generally linear fashion approximately WSW-ENE near the international border with many lobes oriented northwest-southeast. This suggests that the sediments of the Grimsby - Thorold formations are infills within an incision or ravinement that is present on the top of the Cabot Head Formation.

Map 2 also shows a pronounced lobe towards the north is located southeast of Rondeau Harbour and provides the basis for the Morpeth field. Since this lobe appears isolated on the map and does not align itself in the same general pattern as the sediments found to the east, a suggestion can be made that the Morpeth lobe sediments may be separate from those to the east.

Map 3, the Total Grimsby - Thorold Sand Isopach, defines the total sand content of the Grimsby - Thorold formations according to the gamma ray log 100 API unit cutoff. The map suggests that the sands are composed of many lobes which point to the NNW. The thickest sands are located along the international border south of Long Point and in the east central part of Lake Erie south of Dunnville presumably thickening into the United States. The contours of individual sand lobes are commonly closely spaced, parallel, linear curves. This suggests that the sands may have been confined.

The occurrence of the sand body attributed to amalgamated storm deposits in the Upper Cabot Head Formation is advantageous in correlations. Using well logs and cores, a cross-section was drawn to observe the position of the sand body in relation to the base of the Grimsby Formation (Figure 41). In Map 1, as well as the cross-section, the thickness of the sediments between the top of the Reynales - Irondequoit formations and the top of the Queenston Formation remain relatively constant whether or not the Grimsby - Thorold formations are present; the thickness of the sediments does not change with variation of the thickness of the Grimsby - Thorold formations. The cross-section of Figure 41 illustrates that the base of the Grimsby Formation incises into the underlying

Cabot Head Formation and demonstrates the incision of the base of the Grimsby into the Cabot Head.

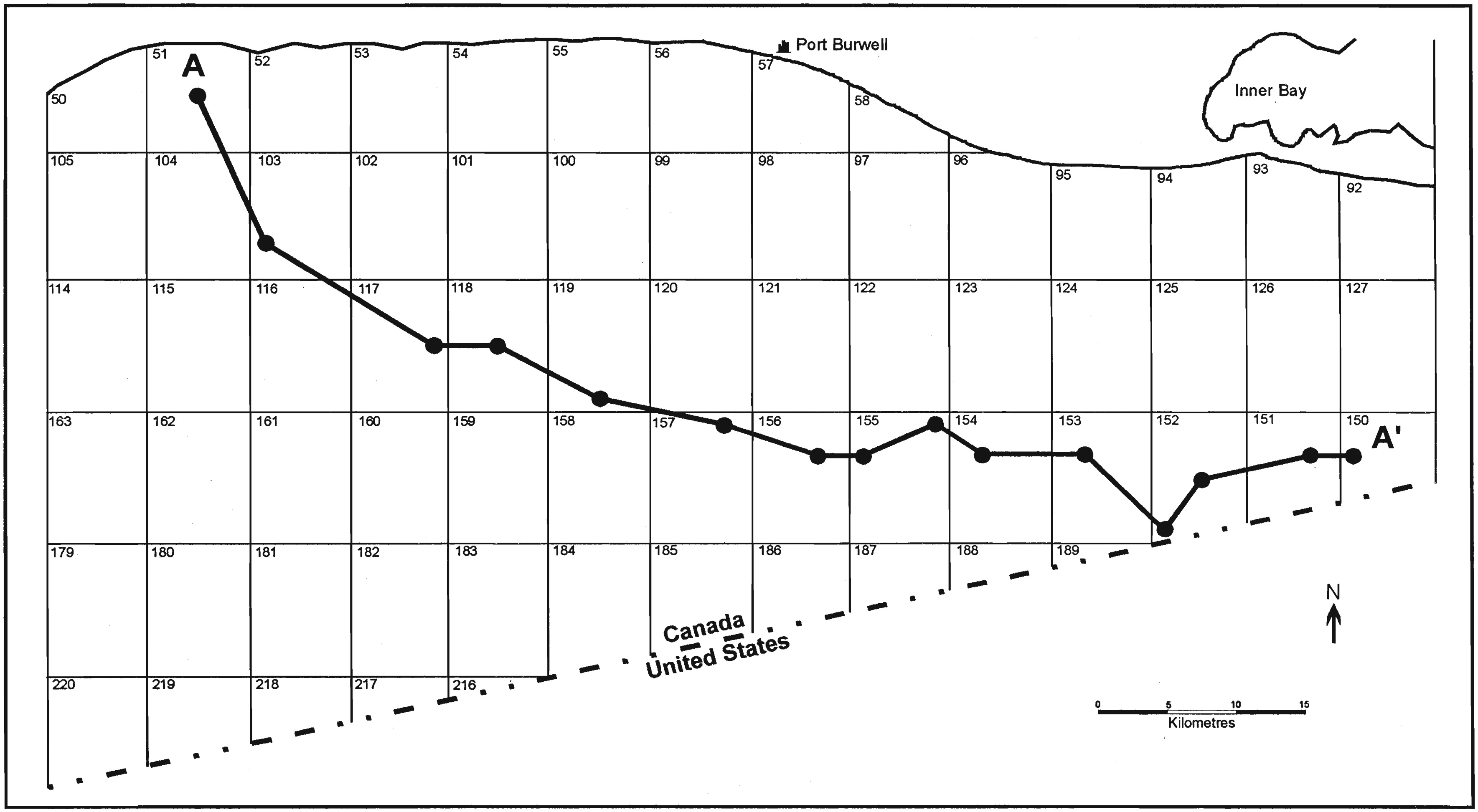
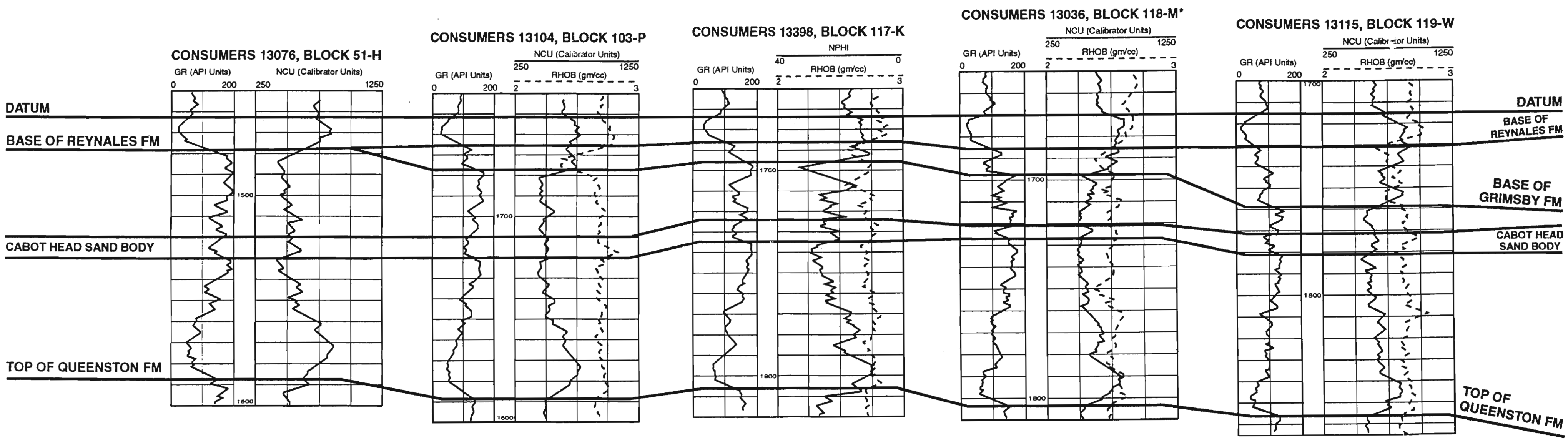
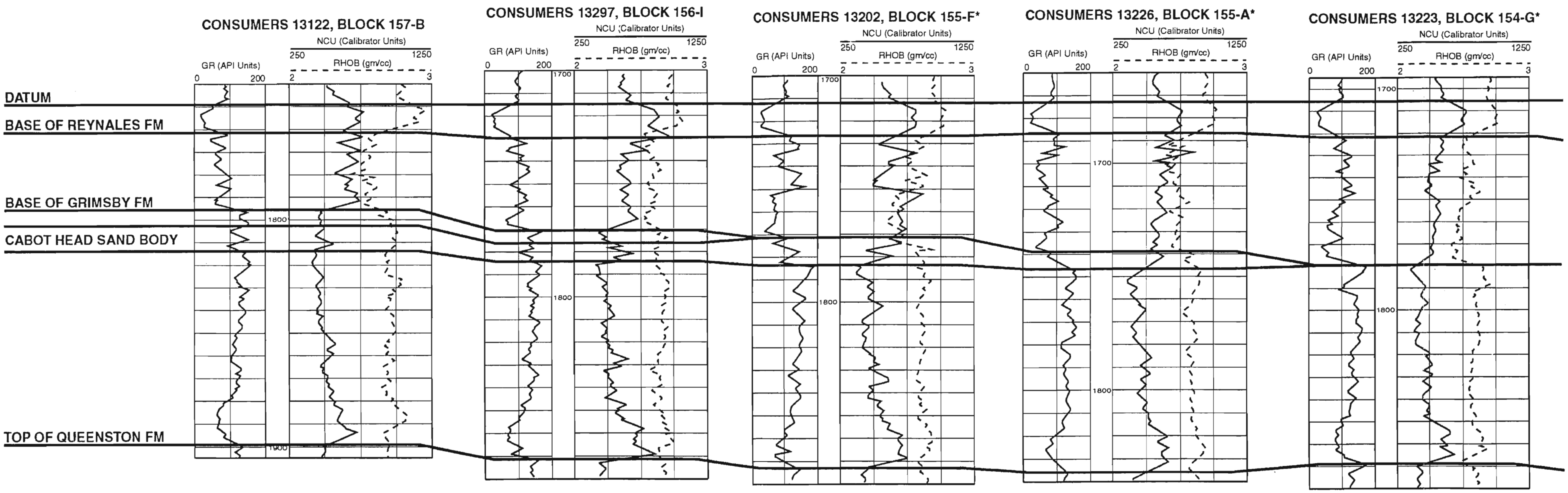


Figure 41: Cross-section A - A' illustrating the incision of the Grimsby Formation into the Cabot Head Formation. The far northwest well, Consumers 13076, Block 51-H, is beyond the subcrop limit of the Grimsby Formation. The Grimsby Formation is thinnest in wells in Blocks 103, 117 and 118 and thickens towards the east where its maximum thickness in this cross-section is in Blocks 152, 151 and 150. The Cabot Head sand body has been correlated along the cross-section and, in some cases (i.e. Consumers 13223, Block 154-G; Consumers 13167, Block 152-N; Consumers 13838, Block 151-I), has been completely removed by the Grimsby Formation incision. Vertical scales are in feet; no horizontal scale is implied except above. Asterisk indicates that a core section is available - see Appendix.

A


CONSUMERS 13076, BLOCK 51-H
CONSUMERS 13104, BLOCK 103-P
CONSUMERS 13398, BLOCK 117-K
CONSUMERS 13036, BLOCK 118-M*
CONSUMERS 13115, BLOCK 119-W
GR (API Units)
NCU (Calibrator Units)
NPHI
RHOB (gm/cc)
DATUM
BASE OF REYNALES FM
BASE OF GRIMSBY FM
CABOT HEAD SAND BODY
TOP OF QUEENSTON FM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CONSUMERS 13297, BLOCK 156-I
CONSUMERS 13202, BLOCK 155-F*
CONSUMERS 13226, BLOCK 155-A*
CONSUMERS 13223, BLOCK 154-G*
GR (API Units)
NCU (Calibrator Units)
RHOB (gm/cc)
DATUM
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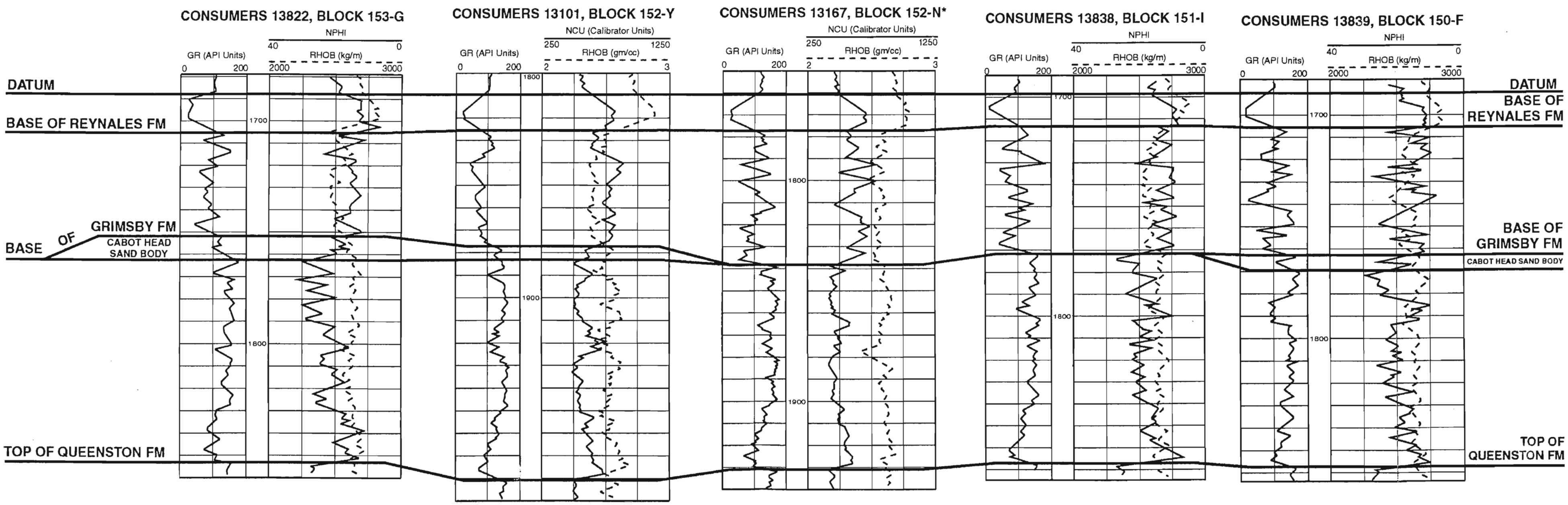
BASE OF GRIMSBY FM
CABOT HEAD SAND BODY
TOP OF QUEENSTON FM

A'


CONSUMERS 13822, BLOCK 153-G
CONSUMERS 13101, BLOCK 152-Y
CONSUMERS 13167, BLOCK 152-N*
CONSUMERS 13838, BLOCK 151-I
CONSUMERS 13839, BLOCK 150-F
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NPHI
RHOB (kg/m)
NCU (Calibrator Units)
RHOB (gm/cc)
DATUM
BASE OF REYNALES FM
BASE OF GRIMSBY FM
CABOT HEAD SAND BODY
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PALEOENVIRONMENT OF THE GRIMSBY - THOROLD FORMATIONS

A ravinement surface was incised into the previously deposited marine shales and thin, very fine to fine grained sandstones, of the storm-dominated Cabot Head Formation after a regression of the sea. The deposits of the Grimsby - Thorold formations represent the deposits following a transgression into these valleys and are the sediments of a shallow marine, tidally influenced, nearshore environment along a northeast-southwest prograding shoreline (Duke *et al.*, 1991). In the lower half of the Grimsby Formation, prograding subtidal, shoreface deposits were incised by subtidal channel complexes oriented approximately in a northwest-southeast direction (Map 2), roughly perpendicular to the trend of the shoreline as suggested by Duke *et al.* (1991). In the middle and upper Grimsby, the facies changes from incising subtidal channels to shallow, discrete tidal channels and mud flats. Sand deposition was primarily in the central portions of the previously incised channels with muds deposited on the flanks (Map 3). Continued shoreline progradation resulted in the deposition of the non-marine, ripple cross-laminated Thorold Formation which was dominated by unidirectional currents. Siliciclastic deposition ended with a major transgression that reworked the Thorold Formation and resulted in the deposition of the argillaceous carbonates of the Reynales and Irondequoit formations.

Earlier attempts at suggesting a paleoenvironment for the Grimsby - Thorold succession suggested a deltaic origin (Sanford, 1969; Martini, 1971; others). In a delta, deposits prograde outwards into standing water normally leaving much thicker sediments near the fluvial source (Blatt *et al.*, 1980). Within a delta, muds deposited offshore as prodelta deposits would normally be succeeded by coarser grained silts and sands creating a generally coarsening upwards sequence as the delta progrades onto the shelf. This is not common within the Grimsby - Thorold formations where the base of the Grimsby Formation is normally marked by a lag deposit followed by a generally fining upwards succession of sandstones overlain by interbedded sandstones and shales. These deposits are normally directly above the marine shales, sandstones and fossiliferous sandstones of the Cabot Head Formation. No muds were observed in any cores that could be correlated to the base of the Grimsby Formation. The only portion of the succession where it commonly becomes slightly coarser is near the upper boundary of the Grimsby - Thorold where it is possibly nearshore in origin. This suggests that the Grimsby - Thorold formations are the result of an infilled incision along a prograding shoreline. As the incision infills, sediment becomes finer grained and eventually the prograding fluvial source of sediment deposits slightly coarser sediment over the previously deposited marine and mixed marine-fluvial portions of the estuary.

As well, on a stable shelf, one would expect to find the thickness of underlying, pre-deltaic sediments to remain generally constant beneath the delta complex as they would further out into the basin away from deltaic deposition. However, the thickness of the combination of the underlying sediments and the deltaic deposits would not be constant but increase near the fluvial source (Blatt *et al.*, 1980). Even in a high-destructive delta (tide- or wave-dominated), where marine processes predominate and redistribute sediment over a much wider area than in a fluvial-dominated delta, one would still expect a thickening of deposits towards the head or fluvial source as well as deposition of muds further out. Figure 41 and Map 1 and Map 3 suggest that the sediment thickness for the Cataract Group remains constant whether the Grimsby - Thorold Formations are present or not. It is unlikely that a deltaic setting would produce this sequence of deposition. One would expect a thickening towards the east and this is not the case.

Estuarine deposits are usually related to a submergence or a transgression (Reinson, 1992) and such modern environments reflect a tripartite zonation from marine to mixed marine-fluvial to fluvial processes (Dalrymple *et al.*, 1992; Figure 42). They can be wave or tidally dominated as well as primarily fluvial or marine influenced. In a tide-dominated estuary, tidal current energy exceeds wave energy at the mouth. The mixed marine-fluvial zone of this type of estuary is much more energetic than in wave-dominated estuaries as tides tend to reach further into the estuary than waves. Therefore, the tripartite zonation of tide-dominated estuaries is not as well developed as in wave-dominated estuaries, and sands occur along the entire length of the estuary (Dalrymple , 1992). The finest deposits still occur at the point of lowest energy and muddy sediments accumulate primarily in tidal flats and marshes along the margins of channels and the estuary. Allen (1992) suggests that the strongest tendencies in tide-dominated estuaries are toward fining-upward sequences and laterally fining toward the estuary margins, with most being sand-dominated.

Subtidal channel complexes of estuarine deposits are dominated by channel facies influenced by tides and typically display abrupt variations in sediment texture and composition, and in physical and biogenic sedimentary structures (Frey and Howard, 1986). Main channels within the complex display diagnostic, estuary-related sedimentary features such as common mud drapes and, less commonly, mud couplets, dominant large scale cross-bedding, common sharp erosional bases with lag deposits of rip-up clasts and are typically overlain by sediments that fine upwards (Rahmani, 1988).

The facies comprising the Grimsby-Thorold formations appear to fit the estuarine model and tripartite zonation as proposed by Dalrymple *et al.*, (1992) and shown in Figure 42. The zonation consists of a marine influenced component which is farthest seaward, a mixed marine-fluvial component and a fluvial component farthest landward. Facies B, the

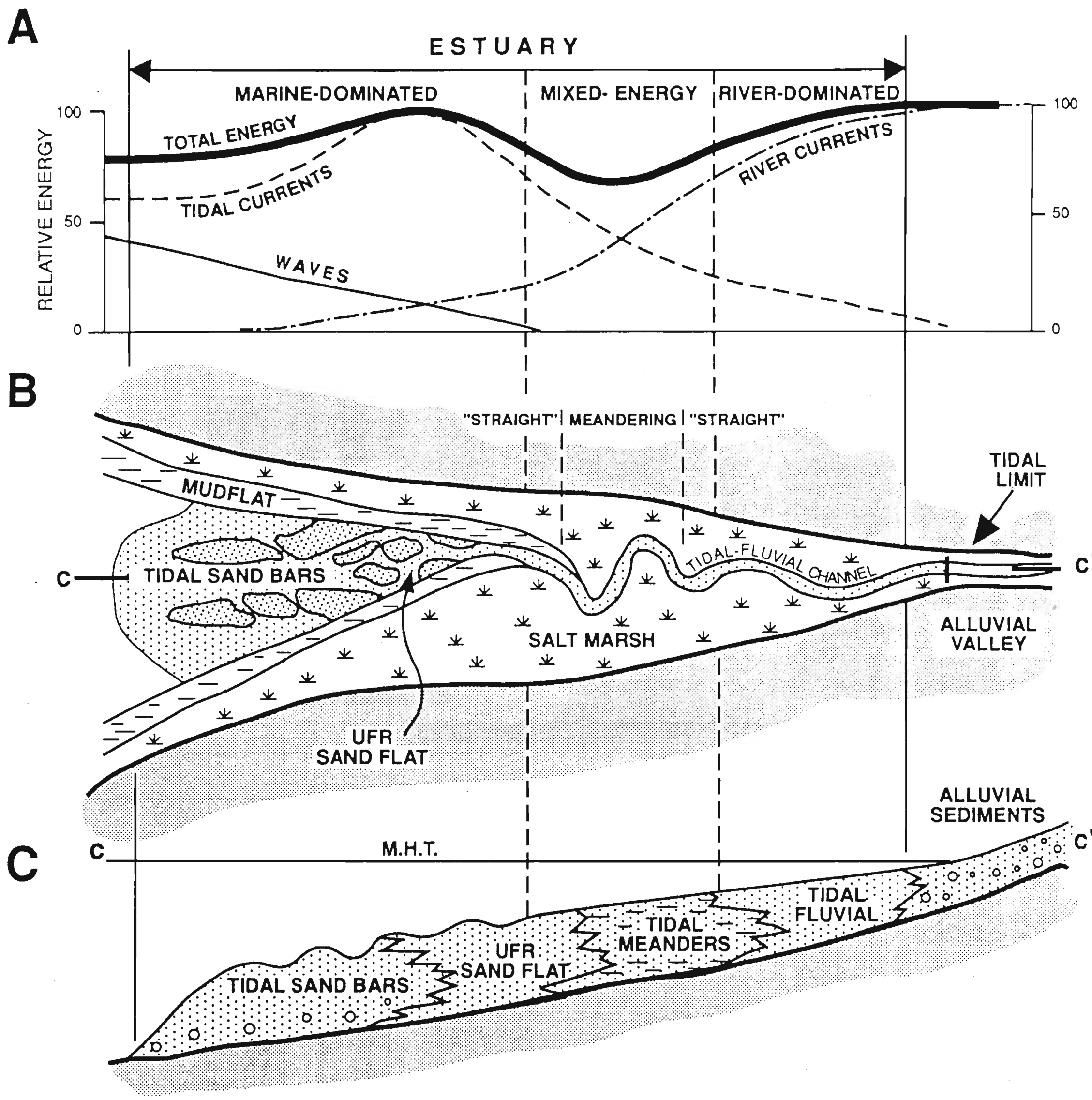

Figure 42: Schematic of tide-dominated estuaries - distribution of **A**) energy types, **B**) morphological elements in plan view, and **C**) sedimentary facies in longitudinal section within an idealized tide-dominated estuary. URF = upper flow regime; M.H.T. = mean high tide. The section in C is taken along the axis of the channel and illustrates the onset of progradation following transgression (Dalrymple *et al.*, 1992).

base of the Grimsby Formation is a fine grained sandstone with large scale cross-bedding, common mud drapes and mud couplets suggesting a tidal influence. As well, a basal lag deposit is present which suggests an erosional or ravinement surface. The facies fines upwards and may represent the farthest seaward extent of the estuary and the marine component. It is overlain by Facies C where sandstones are very fine grained and interbedded sandstones and shales are common. Small scale cross-bedding is common and there are less common mud bundles suggesting less tidal influence and a mixing zone of lower and higher energy. This suggests that Facies C may be the mixing zone between fluvial and marine processes. In modern estuaries, the equivalent of Facies C is composed of small, shallow channels cutting into mud flats (Allen, 1992). Facies C is in turn overlain by the slightly sandier Facies D which exhibits rippled cross-stratification. There are no mud couplets which suggests that there was no tidal influence. Palynology suggests Facies D was deposited in a non-marine environment, which would correspond to the farthest landward extent of the estuary which is typically fluvial.

Estuaries are commonly associated with incised, V-shaped valleys. An example which illustrates this feature is the Albian estuarine deposits of the Peace River Formation in northwestern Alberta (Leckie and Singh, 1991). The coast of German Bay (Helgoland Bight) of the North Sea is comprised of subtidal to intertidal flats and subtidal shoals which are dissected by numerous straight and sinuous channels trending nearly perpendicular to the shoreline (Reineck and Singh, 1980). Three estuaries incise into the coastal, intertidal flats and shoreface deposits further offshore (Figure 15). The thalwegs of the larger channels are incised into shoreface deposits with channel depths up to 15 m. Duke *et al.* (1991) proposed that this system is representative of the Grimsby Formation. This study supports their suggestion and the tidal channel complexes may represent the fringes of estuarine systems located to the south, southeast and east of the study area.

With the shoreline possibly being to the south, southeast and east of the study area, it is possible that the source area for sediment was in this direction as well and may have been associated with the continuation of the Taconic Orogeny which was ongoing into the Early Silurian (Middleton, 1987). The Tuscarora Formation of central and southern Pennsylvania, Maryland and eastern Virginia has been correlated as the lateral equivalent of the Cataract Group (Table 4) and lies to the southeast. Yeakel (1962) suggested that the Tuscarora Formation is of fluvial origin with a small marine component near its upper boundary. Yeakel (1962) described the paleoslope of the area as being towards the northwest, therefore dipping into the study area. The source of Tuscarora sediment was from the southeast and was transported to the northwest via braided river systems. These braided river systems may have extended into the study area and have been the source of sediment for the Cataract Group as well as the Tuscarora Formation. Both Yeakel (1962) and Duke *et al.* (1991) suggest a paleoshoreline to the east of the study area in western New York which turned to the southeast and paralleled the modern Lake Erie shoreline slightly to its south. As well, Yeakel (1962) describes the Tuscarora Formation as primarily thin to thick bedded quartz sandstones and quartz pebble conglomerates. The composition of the Grimsby - Thorold formations is primarily subangular quartz arenites suggesting a similar source.

CONCLUSION

The Grimsby - Thorold formations are the result of nearshore estuarine processes influenced by tides on a prograding shelf; the package includes subtidal channel complexes, discrete tidal channels, mud flats and non-marine deposits. Deposition was related to a regressive - transgressive cycle associated with eustatic sea level change, possibly caused by the melting and resurgence of continental glaciation centred in Africa in the Late Ordovician/Early Silurian. During a transgression, incision occurred and Grimsby deposition began during the subsequent regression with the deposition of subtidal channel complexes incised into the marine deposits of the Cabot Head Formation. These deposits dominate the lower half of the Grimsby. Deposition continued with a change from these subtidal channel complexes to laterally migrating, discrete, shallow tidal channels and mud flats. These were in turn overlain by the non-marine deposits of the Thorold Formation. Grimsby - Thorold deposition ended with a major transgression replacing siliciclastic deposition with primarily carbonate deposition.

The source of sediment was from the east and southeast and associated with a continuation of the Taconic Orogeny into the Early Silurian. The fluvial head of the estuary prograded from a shoreline that was located in western New York and western Pennsylvania running NNE-SSW and then turning NW-SE, paralleling the present day Lake Erie shoreline.

The facies attributed to the Grimsby - Thorold formations can be ascribed to the three zones within the tripartite zonation suggested by Dalrymple *et al.* (1992) for estuaries, that is, a marine-dominated facies, a mixed energy facies, and a facies that is dominated by fluvial processes. Also, sediments within the Grimsby - Thorold form commonly fining upwards sequences which is common in estuarine settings whereas deltaic deposits are normally composed of coarsening upwards sequences in a vertical wedge shape with coarser material near the head. The only coarsening upwards observed in the study was in the Thorold Formation and attributed to non-marine deposition.

The presence of a lag deposit at the base of the Grimsby - Thorold formations suggests that they were incised into the Cabot Head Formation. Further, the thickness of Early Silurian sediments located between the top of the Queenston Formation, where Early Silurian sedimentation began, to the top of the Reynales - Irondequoit formation are constant whether the Grimsby - Thorold formations are present or not. Also, cross-sections using the sand body located in the Cabot Head Formation for correlation further show that the Grimsby Formation has been incised into the previous deposits of the Cabot Head.

The Grimsby and Thorold Formations of the Cataract Group are economically important to the oil and gas industry of Ontario, representing a large percentage of the gas produced within the province. This thesis has brought together much of the available subsurface information to better understand the sedimentology, paleoenvironment and depositional history of the Grimsby and Thorold Formations to aid in drilling and production.

FURTHER WORK

Further work is encouraged to better understand the Grimsby and Thorold Formations. Since this study was regional in nature, more detailed work is definitely required to better define and delineate the facies of the formations.

The most difficult formation boundary to identify in this study was the Thorold - Grimsby boundary. A better understanding and delineation of the boundary would be most beneficial. The Thorold Formation is considerably different in subsurface than in outcrop and the formation may not actually be present in subsurface. Hence, it was grouped together with the Grimsby Formation in this study. As well, there is confusion in the literature as to whether the Thorold Formation should be included within the Cataract Group below the unconfomity that is present at the top of the Cataract Group (Kilgour, 1963; Martini, 1971; Duke, 1991) or included as part of the Clinton Group above the unconfomity (Sanford, 1969; Brigham, 1971; Winder and Sanford, 1972). This study suggests it should be included as part of the Cataract Group and below the unconformity as opposed to being above the unconformity and part of the Clinton Group. This should be confirmed.

The subsurface work within this thesis should be tied into the numerous outcrop studies along the Niagara Escarpment. Cores from the Niagara Peninsula exist and would aid in this project. With this tie in, cross-sections could be drawn and a complete picture of the Grimsby and Thorold formations and the Cataract Group would be possible.

The Lower Cataract Group, that is the Whirlpool and Manitoulin Formations, was outside the work of this thesis. The Whirpool Formation is important to the petroleum industry as it is a gas producer and a detailed study would aid in hydrocarbon production. These formations should be further delineated in subsurface and the data could then be added to that of this study leaving a consistent database for the entire Cataract Group.

Finally, the palynology included within this thesis suggests that some of the earliest known terrestial landplants existed along the shores of an Early Silurian sea located within the study area. This should be expanded and confirmed.

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APPENDIX:

CORE SECTIONS

LEGEND

Sedimentary Structures

	High Angle Bedding
	Ripple Cross-laminations
	Planar Laminations
	Planar Bedding
	Low Angle Inclined Bedding
	Cross Bedding
	Wavy Bedding
	Flaser Bedding
	Trough Cross-bedding
	Soft Sediment Deformation
	Bioturbation
	Syneresis Crack
	Fault
	Sand Clast
	Mud Clast
	Sandy
HCS	Hummocky Cross Stratification

Ichnospecies

Ar - Arthophycus

Ch - Chondrites

Sk - Skolithos

Te - Teichichnus

Di - Diplocraterion

Pl - Planolites

Minerals

P - Pyrite

Ce - Celestite

Ph - Phosphatic

Gl - Glauconitic

Se - Selenite

- Dolomitic

- Calcareous

Body Fossils

Br - Brachiopod (*Lingula*)

Cr - Crinoid

- Missing Core Section

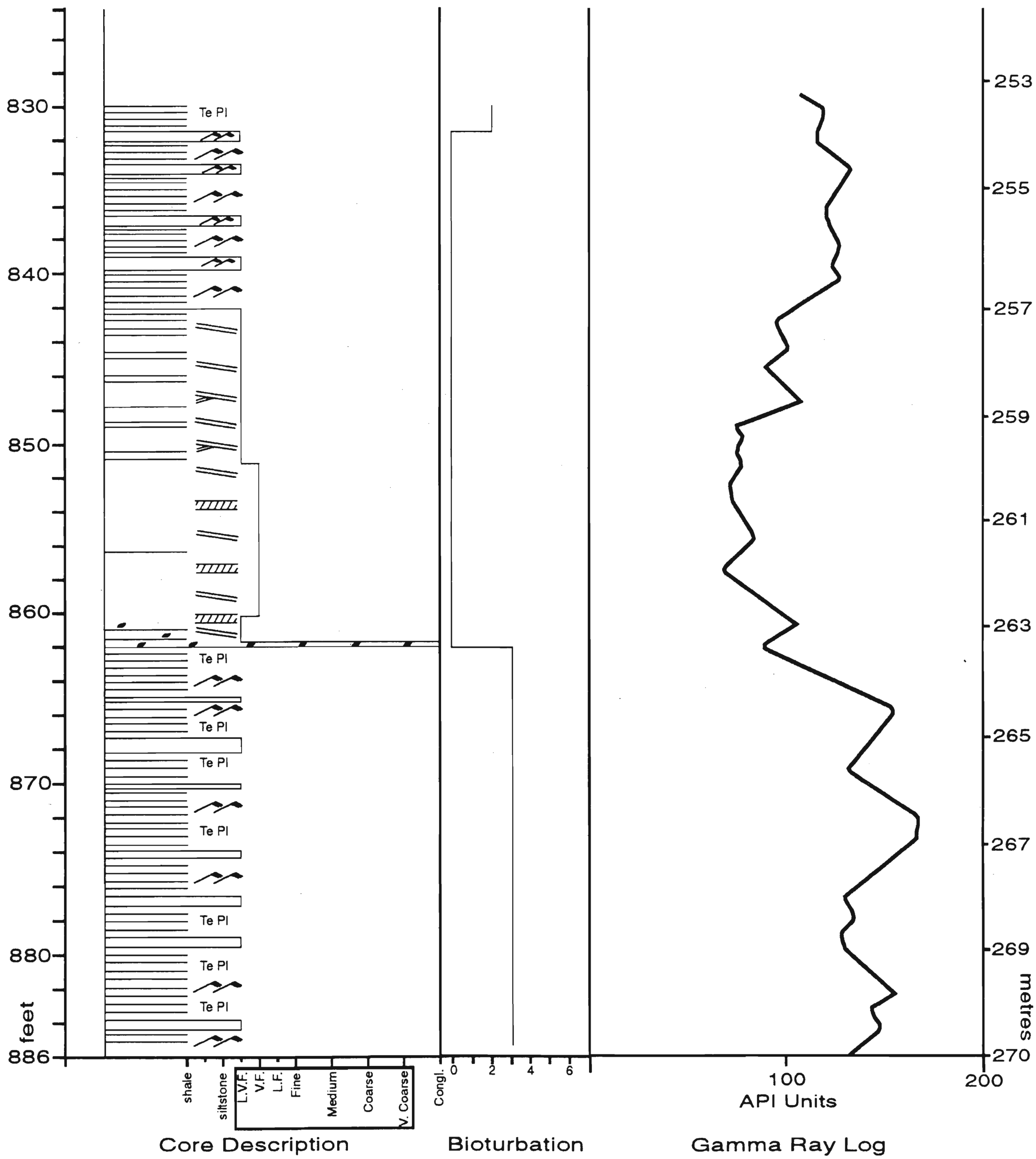
Well Name: Anschutz 8-V
Block Number: 8-V

Latitude: 42 50' 44.362" N
Longitude: 79 26' 14.578" W

Cored Interval: 796.0 - 885.0 ft.
242.6 - 269.7 m

K.B. Elev.: 614 ft. 187.1 m
Pet. Res. Core No.: #679

Page One Interval: 253 - 269.7 m



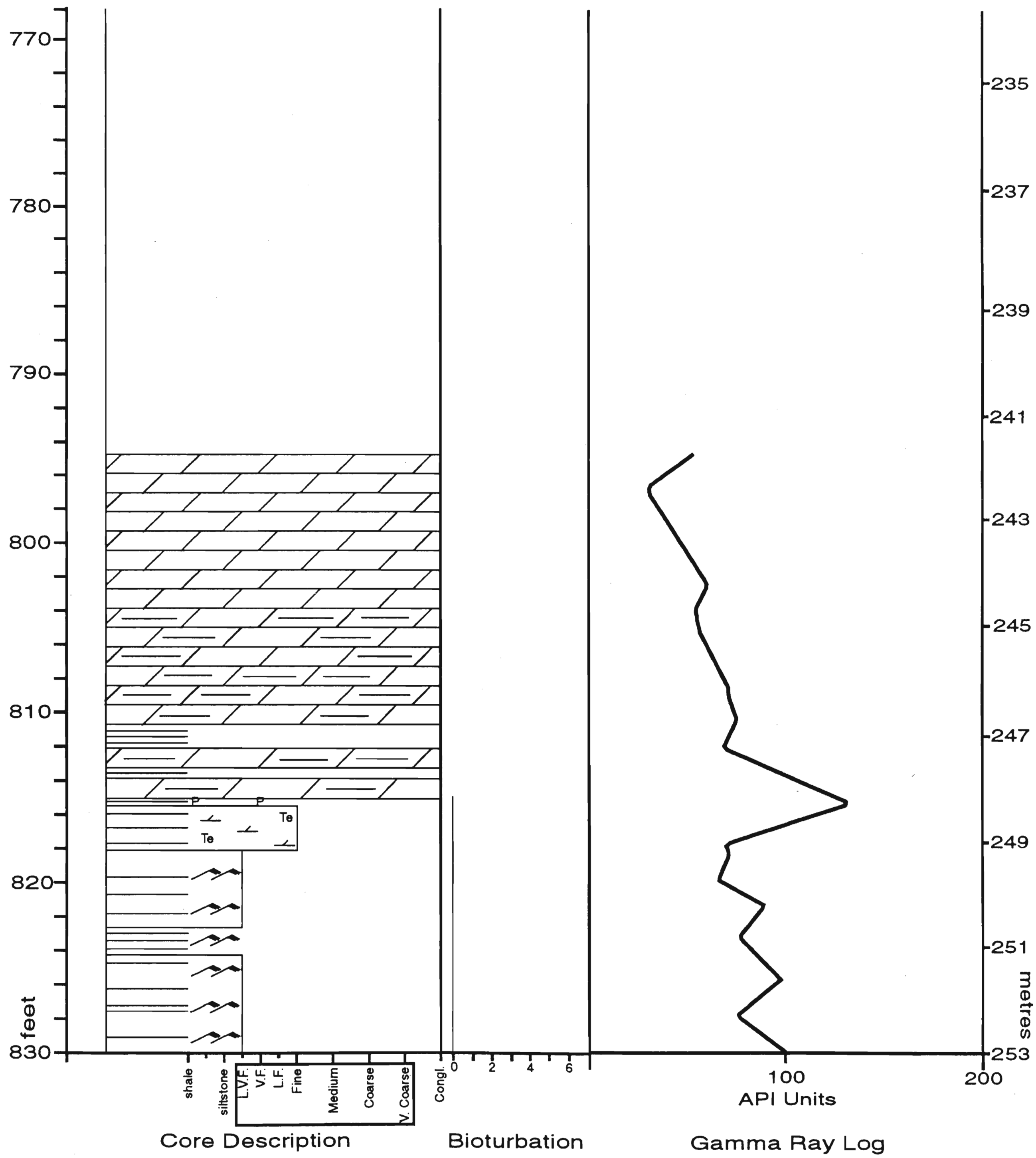
Well Name: Anschutz 8-V
Block Number: 8-V

Latitude: 42 50' 44.362" N
Longitude: 79 26' 14.578" W

Cored Interval: 796.0 - 885.0 ft.
242.6 - 269.7 m

K.B. Elev.: 614 ft. 187.1 m
Pet. Res. Core No.: #679

Page Two Interval: 242.6 - 253.0 m

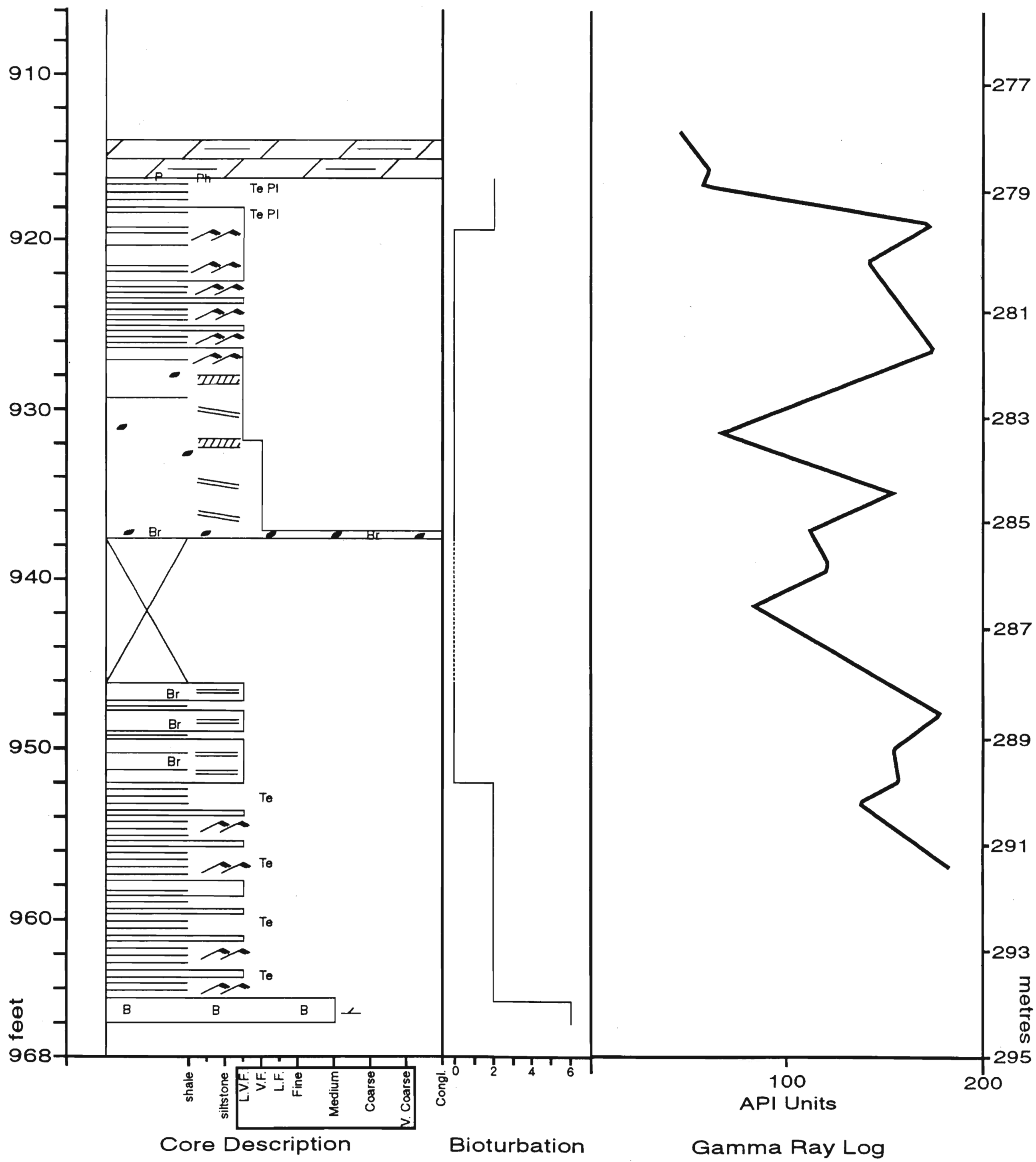


Well Name: Long Point Port Dover #1
Block Number: 14-S

Latitude: 42 46' 18" N
Longitude: 80 11' 57" W

Cored Interval: 914 - 966 ft.
278.6 - 294.5 m

K.B. Elev.: 582 ft. 177.4 m
Pet. Res. Core No.: #112

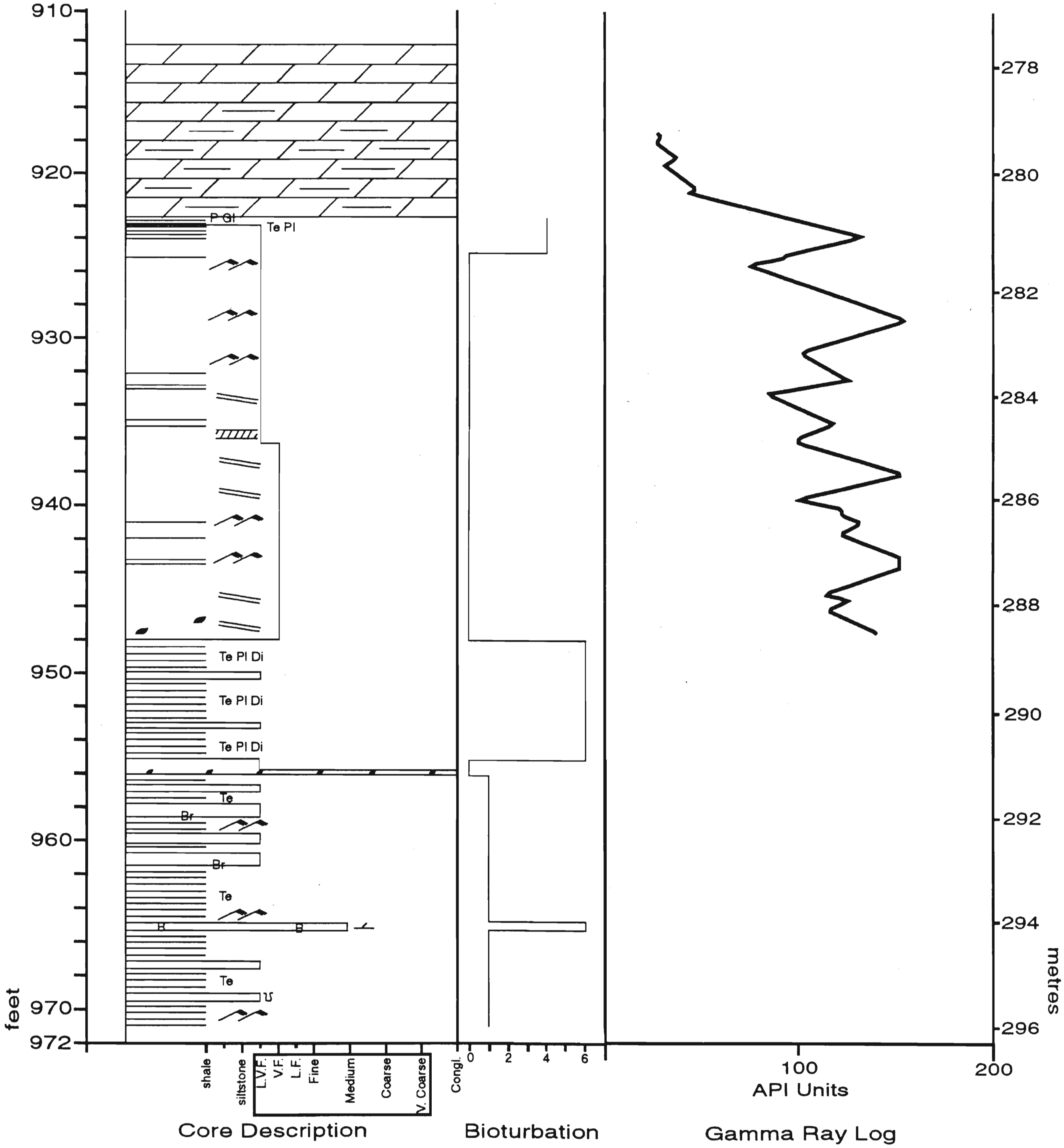


Well Name: Long Point Port Dover #4
Block Number: 14-U

Latitude: 42 45' 44" N
Longitude: 80 10' 50" W

Cored Interval: 912.0 - 971.0 ft.
278.0 - 296.0 m

K.B. Elev.: 585 ft. 178.3 m
Pet. Res. Core No.: #109

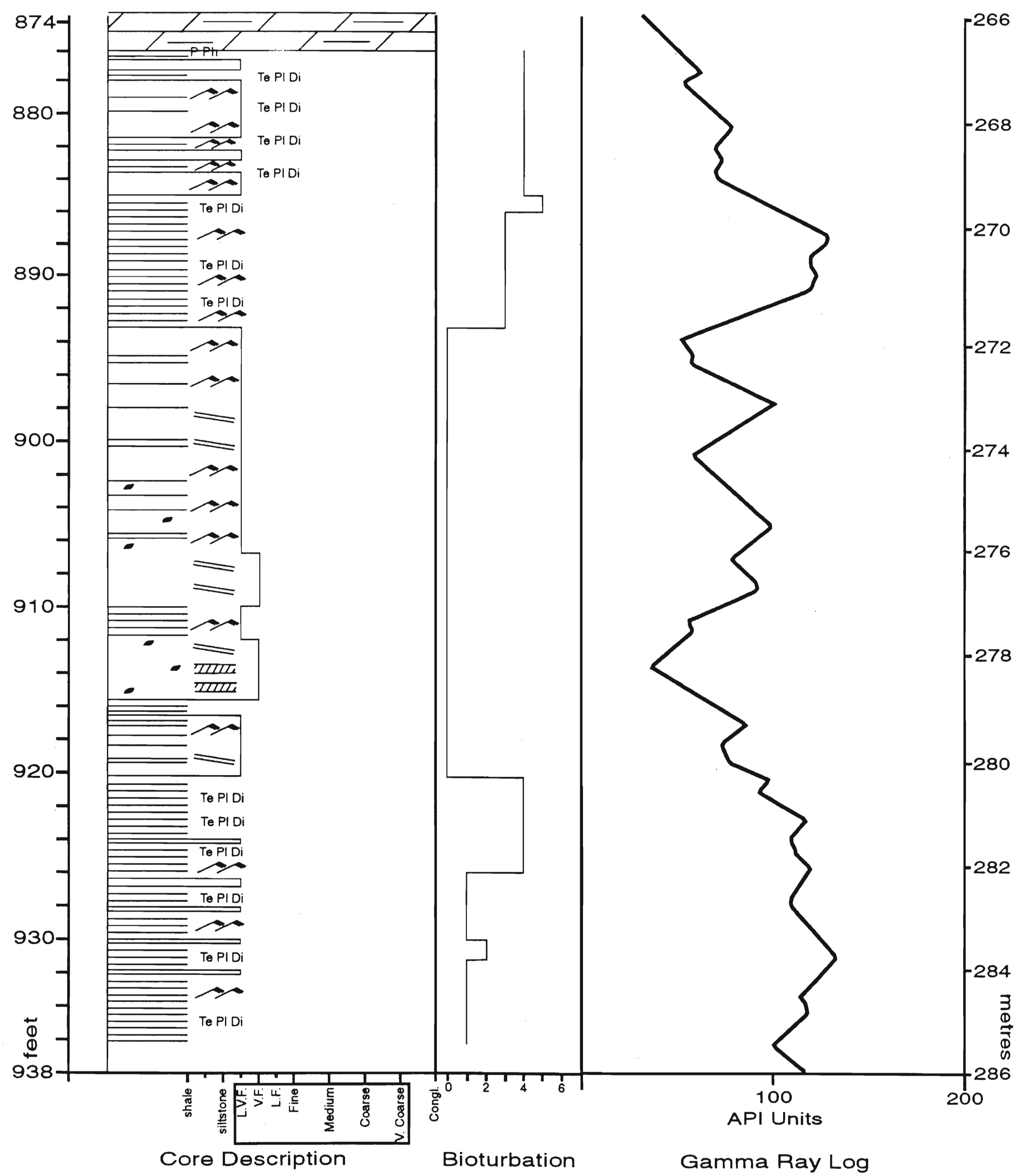


Well Name: Place Anschutz 19-L
Block Number: 19-L

Latitude: 42 47' 45.72" N
Longitude: 79 46' 16.72" W

Cored Interval: 873.0 - 936.0 ft.
266.1 - 297.5 m

K.B. Elev.: 615 ft. 187.5 m
Pet. Res. Core No.: #682

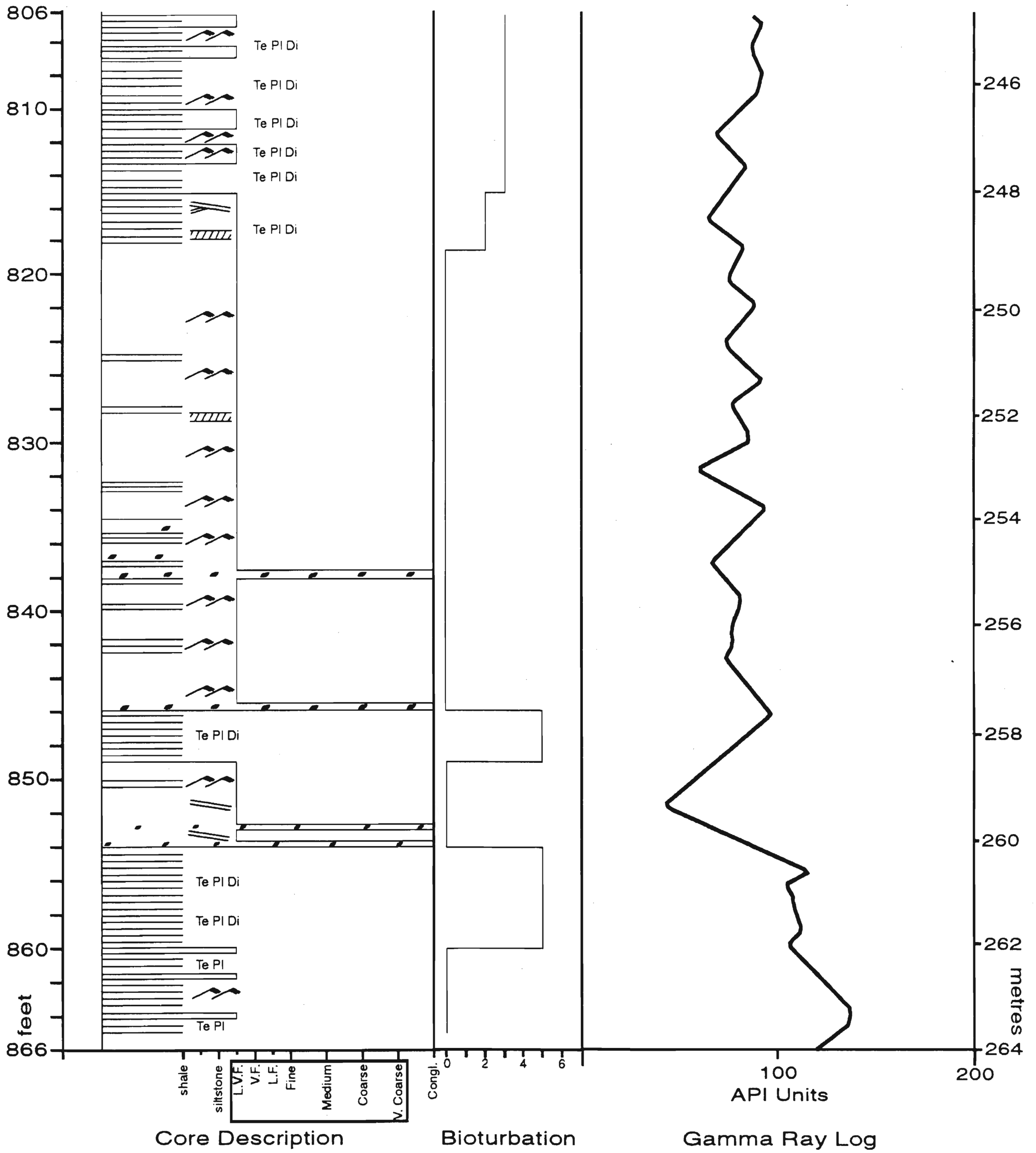


Well Name: Anschutz 20-D
Block Number: 20-D

Latitude: 42 49' 45.17" N
Longitude: 79 43' 14.57" W

Cored Interval: 806.0 - 865.0 ft.
245.7 - 263.7 m

K.B. Elev.: 615 ft. 187.5 m
Pet. Res. Core No.: #609

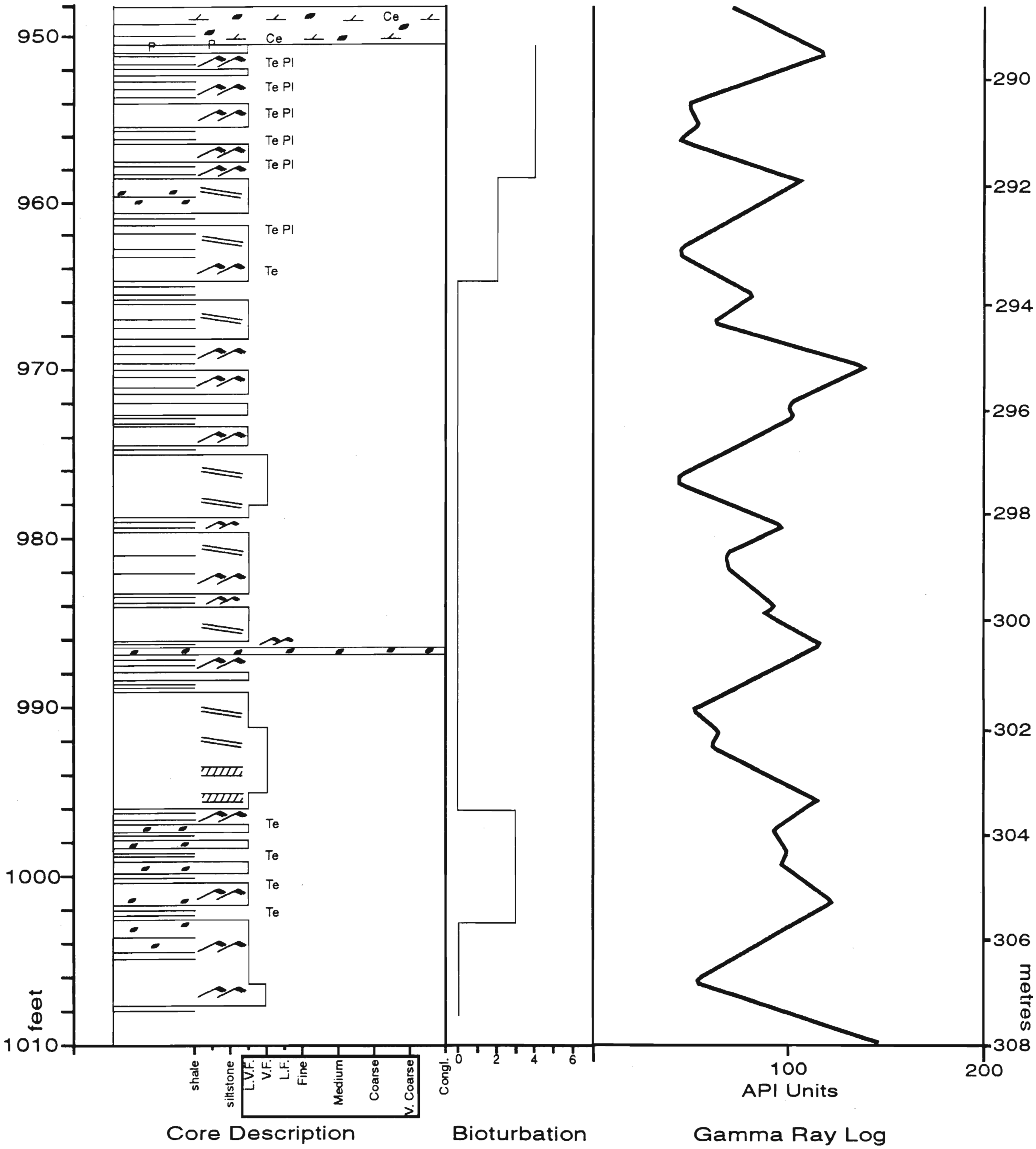


Well Name: Anschutz 21-W
Block Number: 21-W

Latitude: 42 45' 45.05" N
Longitude: 79 37' 28.93" W

Cored Interval: 948.0 - 1008.0 ft.
289.0 - 307.2 m

K.B. Elev.: 614 ft. 187.1 m
Pet. Res. Core No.: #678

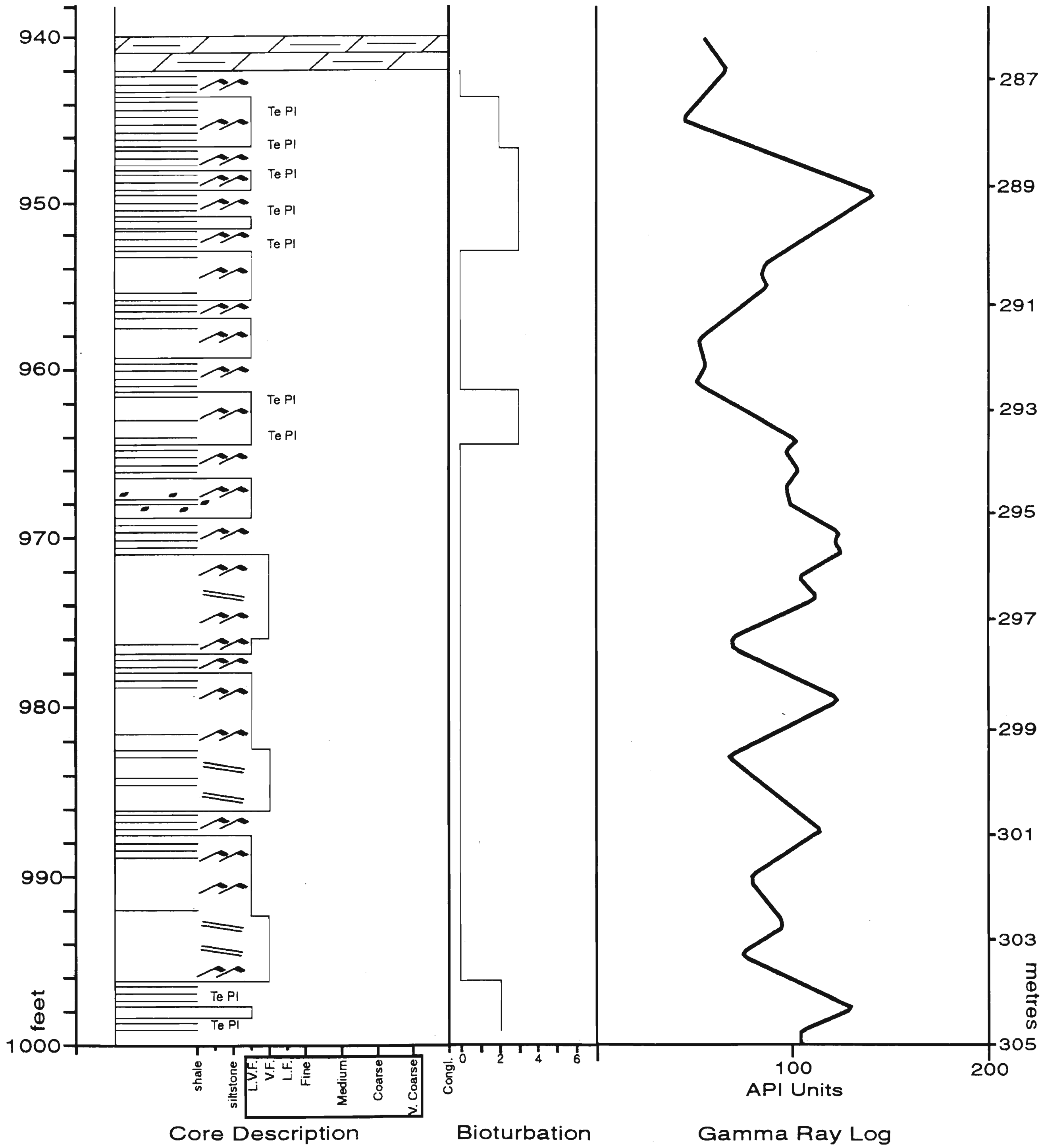


Well Name: Anschutz 23-S
Block Number: 23-S

Latitude: 42 46' 45.239" N
Longitude: 79 26' 14.747" W

Cored Interval: 940.0 - 999.0 ft.
286.5 - 304.5 m

K.B. Elev.: 599 ft. 182.6 m
Pet. Res. Core No.: #680

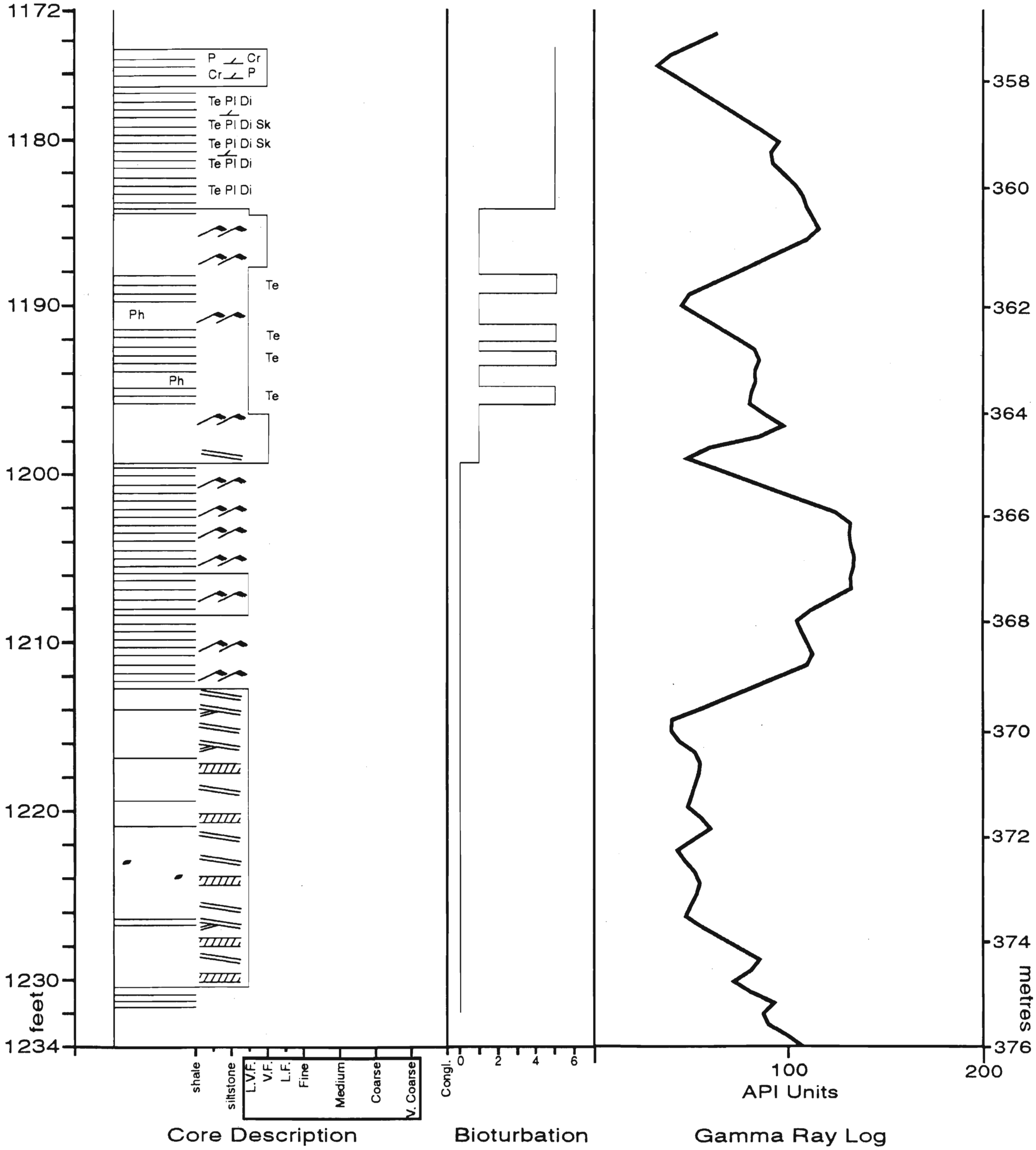


Well Name: Pembina #3 Lake Erie 39-W-3
Block Number: 39-W-3

Latitude: 42 40' 11.41" N
Longitude: 79 32' 47.26" W

Cored Interval: 1174.5 - 1231.3 ft.
358.0 - 375.3 m

K.B. Elev.: 592.8 ft. 180.7 m
Pet. Res. Core No.: #915

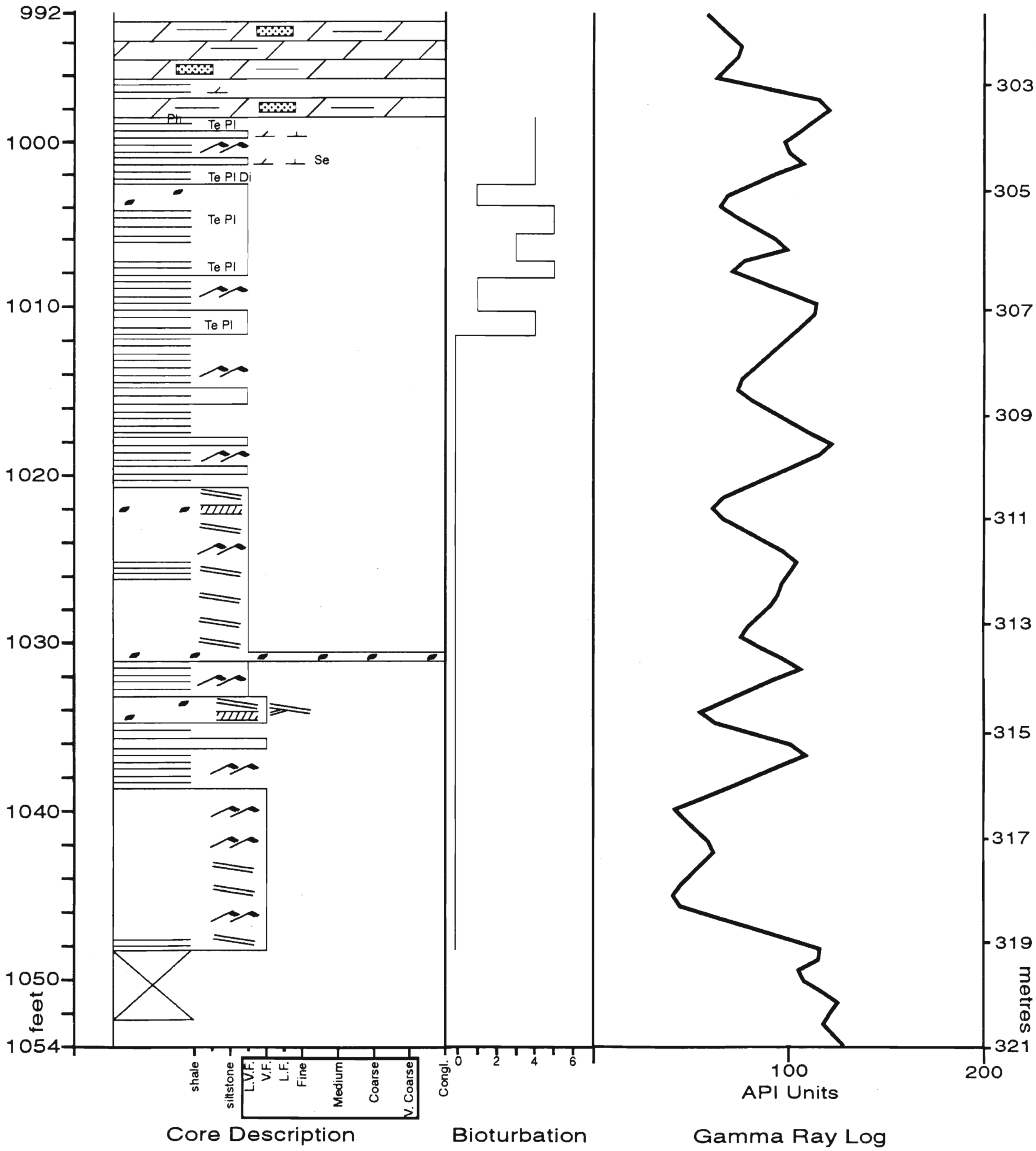


Well Name: Pembina #2 Lake Erie 41-J-2
Block Number: 41-J-2

Latitude: 42 43' 44.05" N
Longitude: 79 40' 46.64" W

Cored Interval: 991.8 - 1052.5 ft.
302.3 - 320.8 m

K.B. Elev.: 593.2 ft. 180.8 m
Pet. Res. Core No.: #869

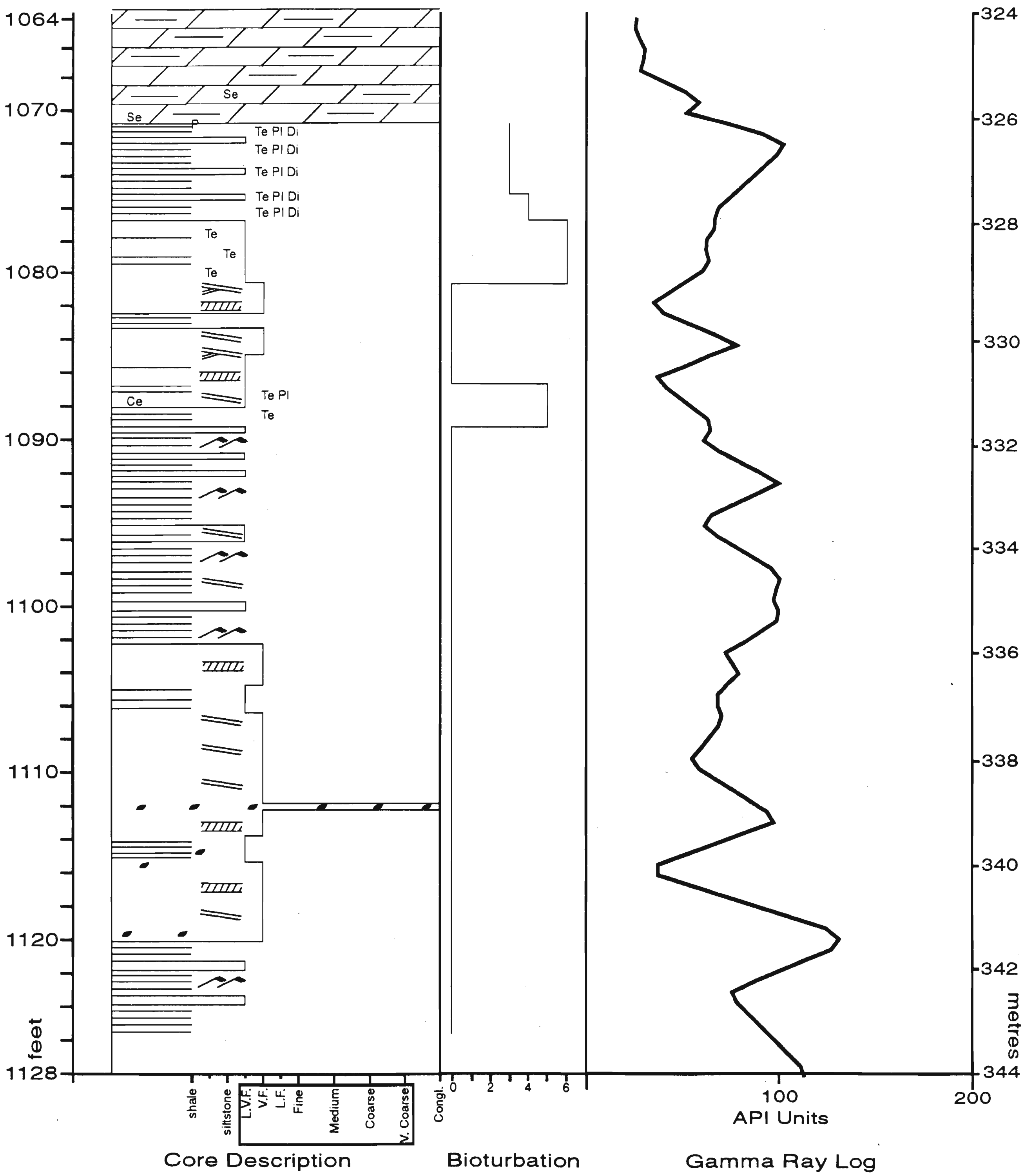


Well Name: Pembina #3 Lake Erie 41-P-3
Block Number: 41-P-3

Latitude: 42 41' 12.15" N
Longitude: 79 44' 47.34" W

Cored Interval: 1063 - 1125.7 ft.
324.0 - 343.1 m

K.B. Elev.: 592.8 ft. 180.7 m
Pet. Res. Core No.: #773

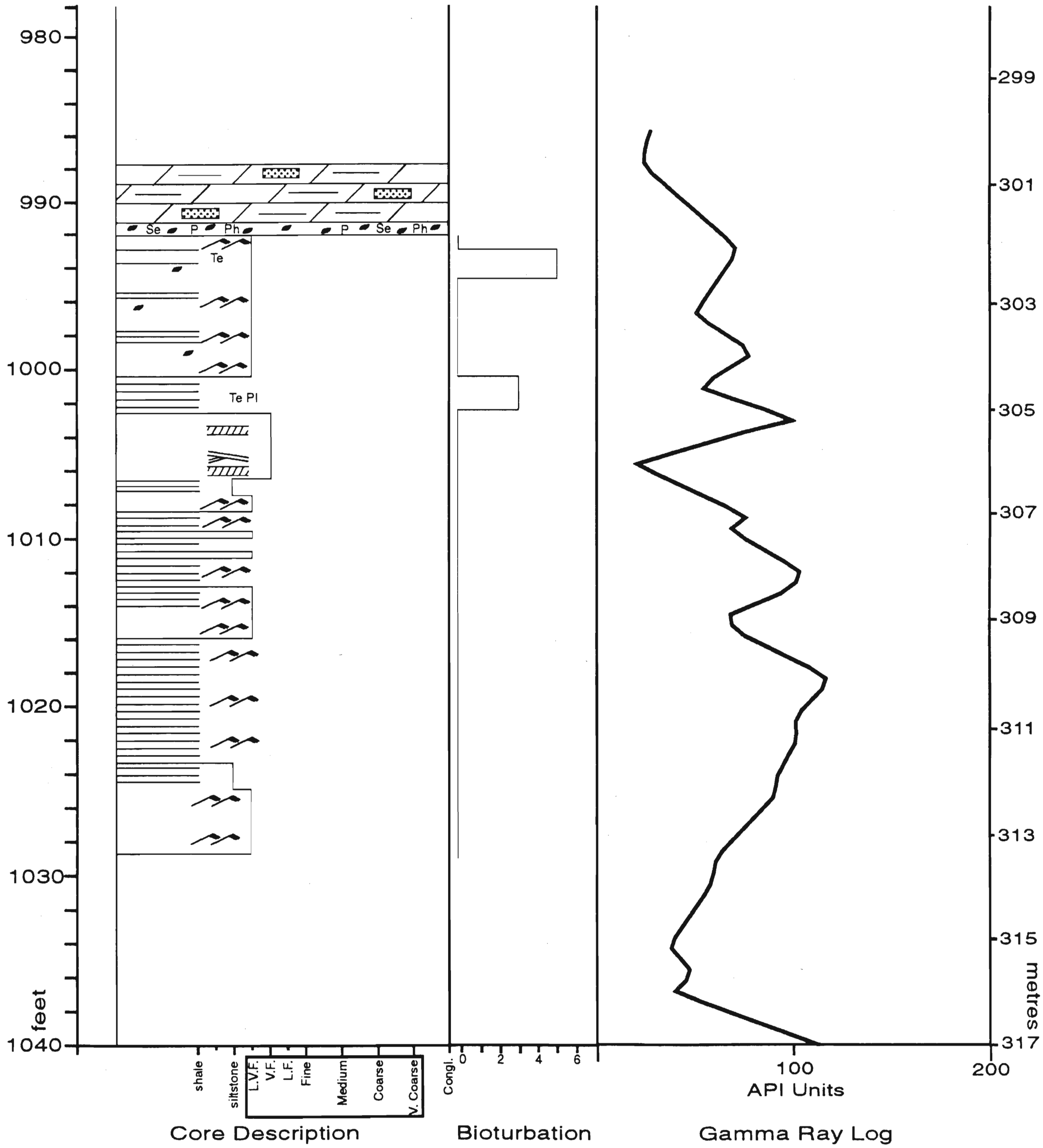


Well Name: Pembina #2 Lake Erie 42-F-2
Block Number: 42-F-2

Latitude: 42 43' 44.705" N
Longitude: 79 49' 46.610" W

Cored Interval: 987.5 - 1028.5 ft.
301.0 - 313.5 m

K.B. Elev.: 593 ft. 180.7 m
Pet. Res. Core No.: #867



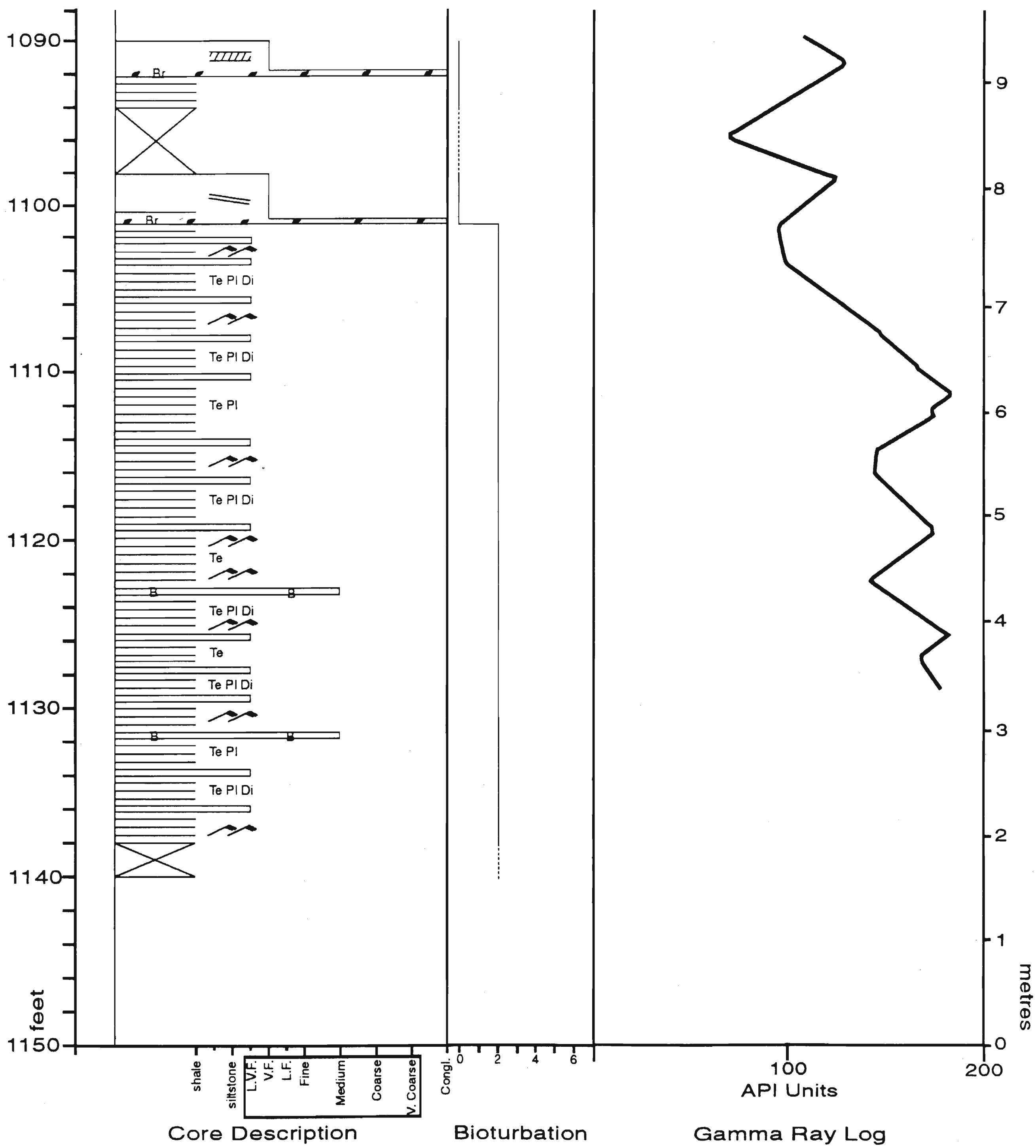
Well Name: Mitchell 750-56
Block Number: 44-S

Latitude: 42 41' 45.5" N
Longitude: 79 56' 13.0" W

Cored Interval: 1050 - 1140 ft.
320.0 - 347.5 m

K.B. Elev.: 597 ft. 182.0 m
Pet. Res. Core No.: #831

Page One Interval: 332.2 - 347.5



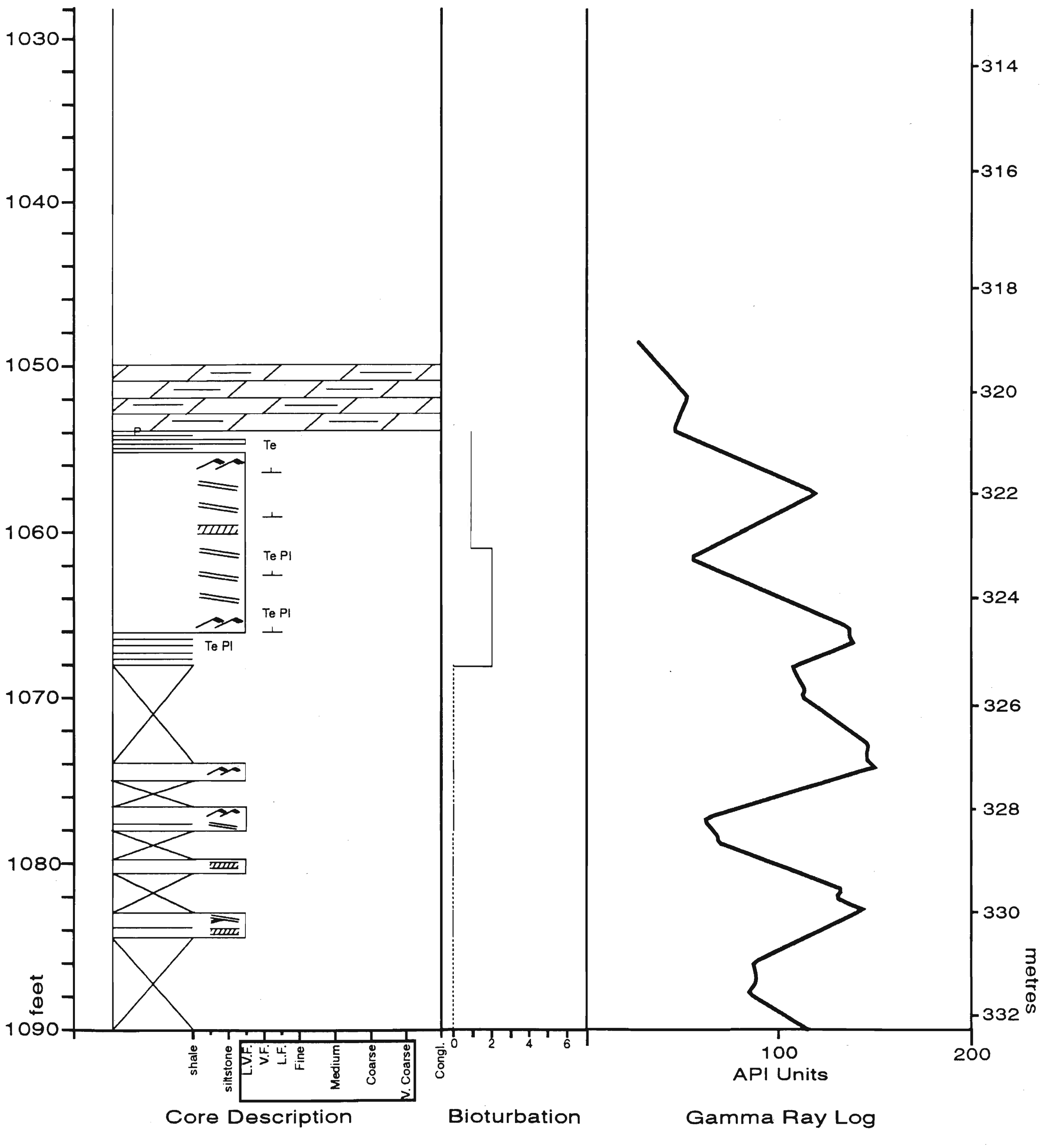
Well Name: Mitchell 750-56
Block Number: 44-S

Latitude: 42 41' 45.5" N
Longitude: 79 56' 13.0" W

Cored Interval: 1050 - 1140 ft.
320.0 - 347.5 m

K.B. Elev.: 597 ft. 182.0 m
Pet. Res. Core No.: #831

Page Two Interval: 320.0 - 332.2

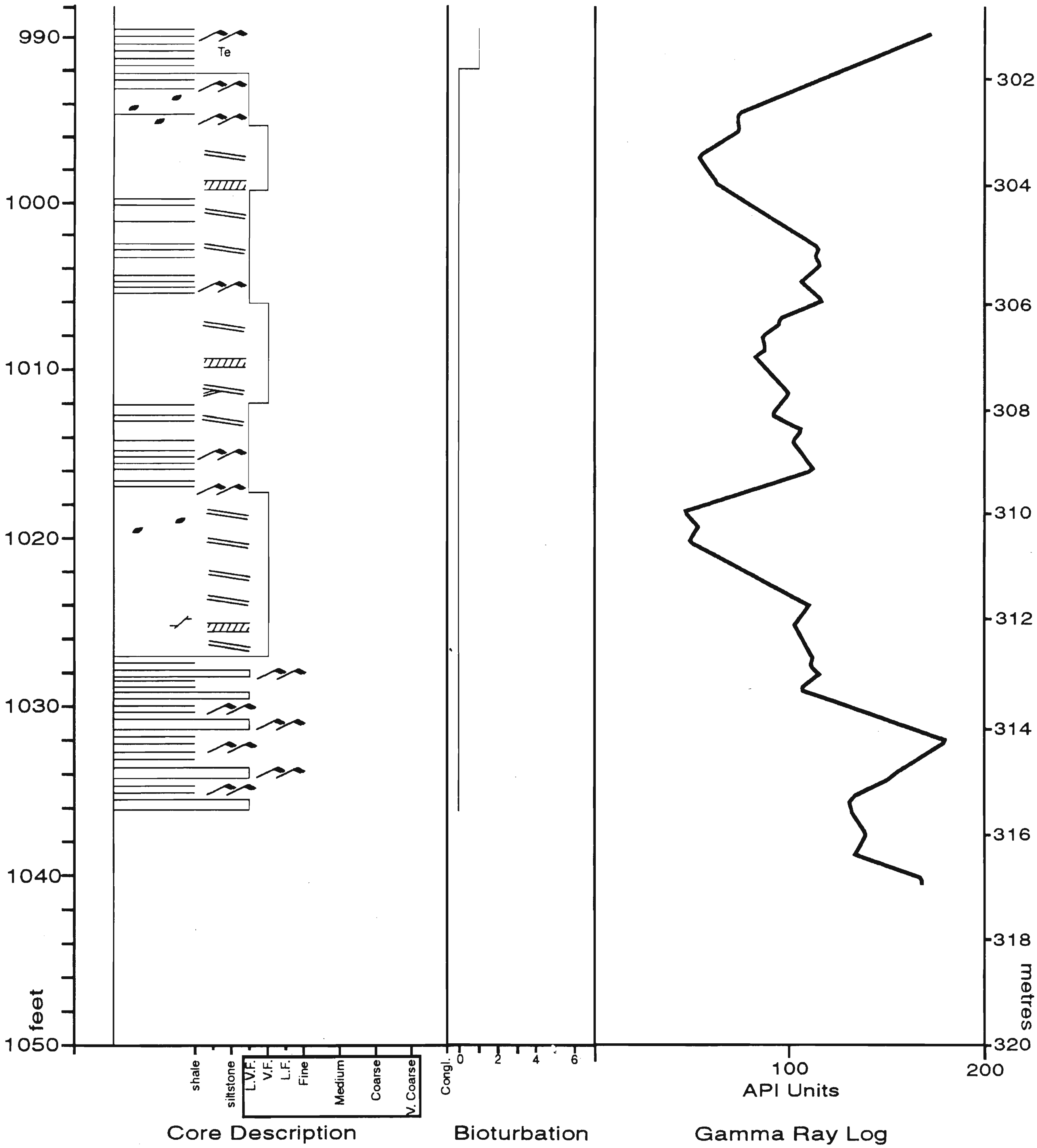


Well Name: Mitchell 623-26
Block Number: 45-N

Latitude: 42 42' 40.9" N
Longitude: 80 03' 49.8" W

Cored Interval: 989.5 - 1036 ft.
301.6 - 315.8 m

K.B. Elev.: 597 ft. 182.0 m
Pet. Res. Core No.: #373

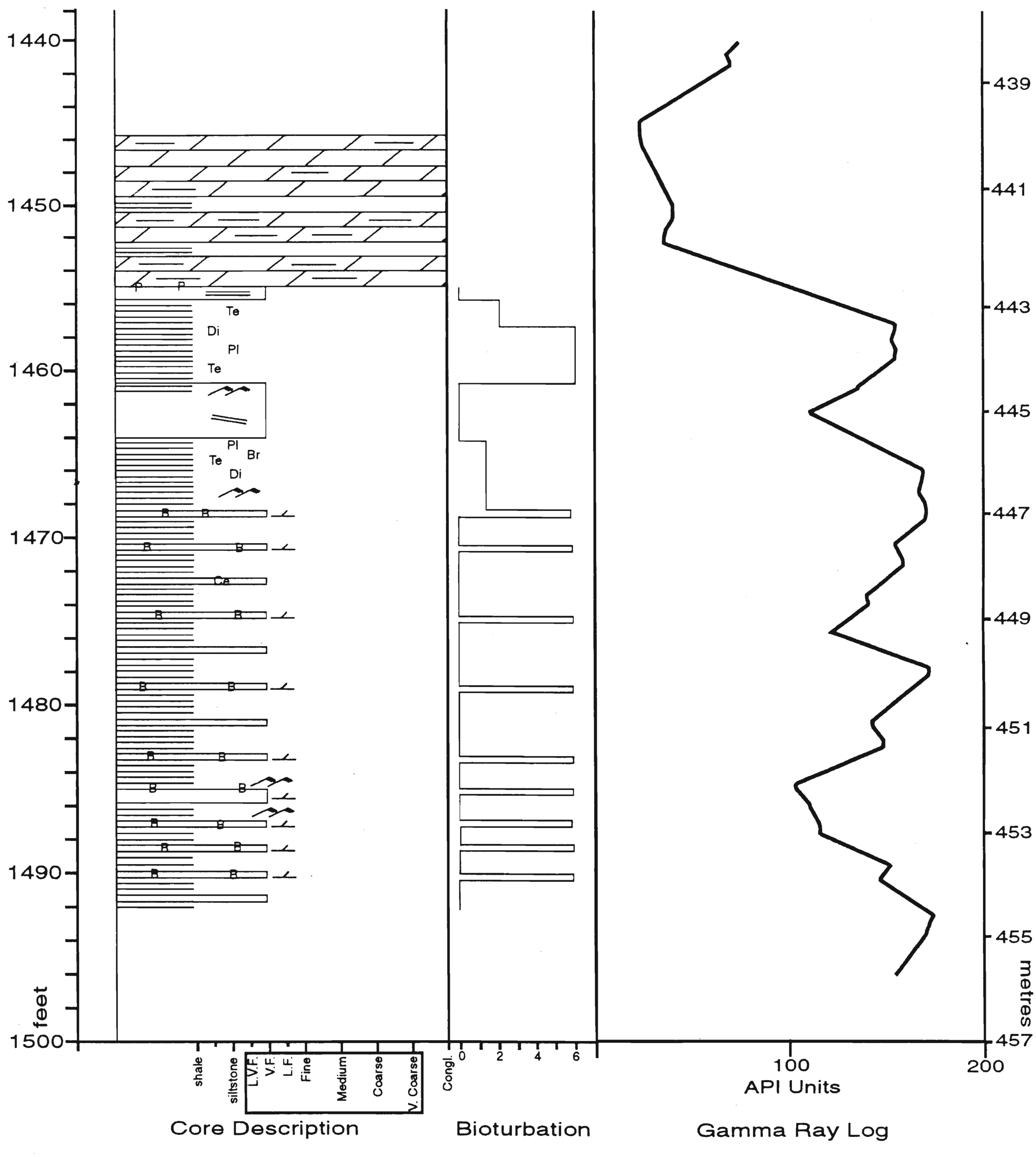


Well Name: Consumers 13315
Block Number: 56-R

Latitude: 42 36' 19" N
Longitude: 80 52' 29" W

Cored Interval: 1446 - 1496 ft. (1492-96 lost)
440.7 - 456.0 m

K.B. Elev.: 616 ft. 187.8 m
Pet. Res. Core No.: #674

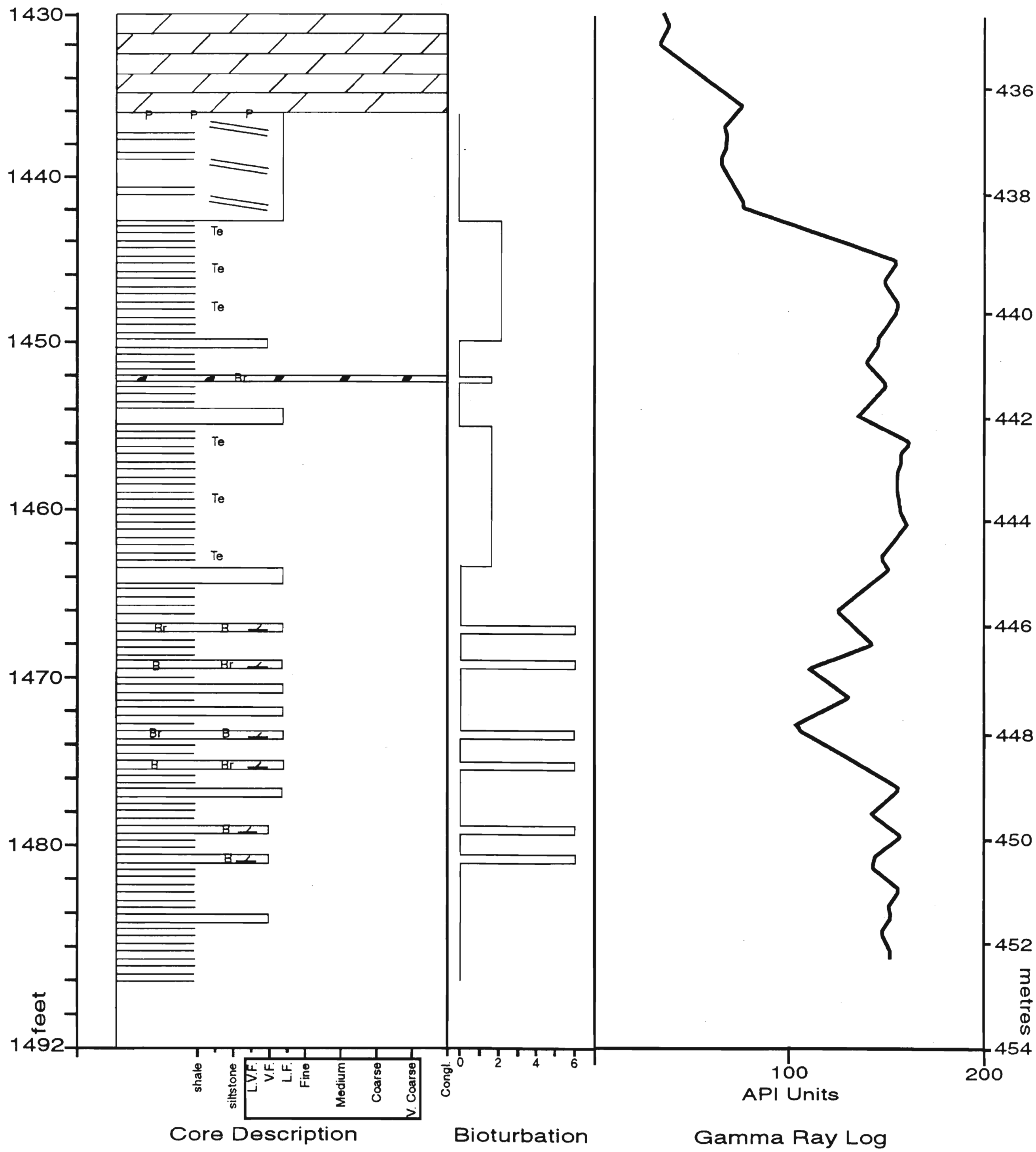


Well Name: Consumers 13316
Block Number: 57-V

Latitude: 42 35' 14.86" N
Longitude: 80 46' 19.58" W

Cored Interval: 1430 - 1490 ft.
435.9 - 453.5 m

K.B. Elev.: 598 ft 182.3 m
Pet. Res. Core No.: #687

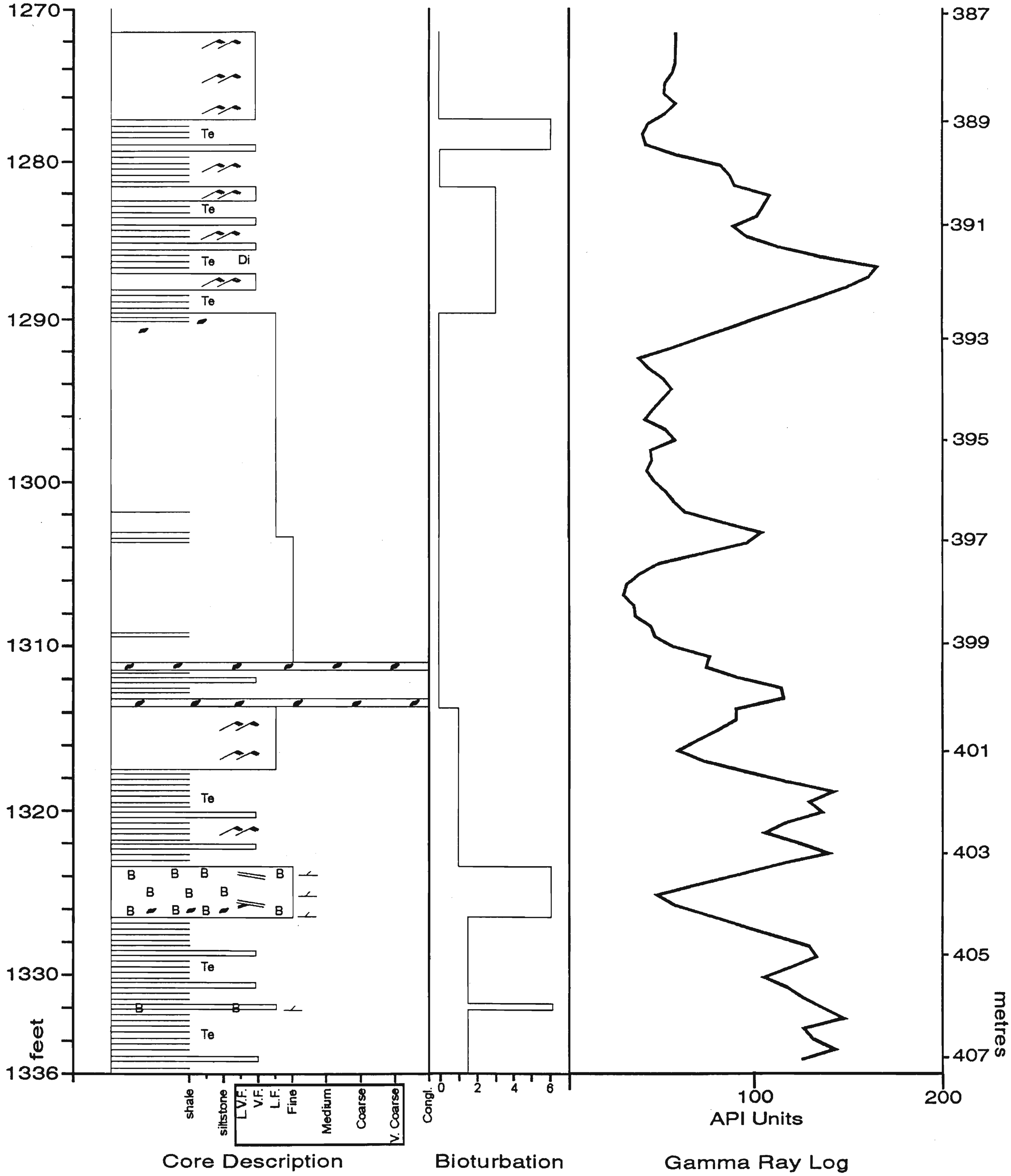


Well Name: Pembina #4 Lake Erie 62-T
Block Number: 62-T-4

Latitude: 42 36' 17.50" N
Longitude: 80 15' 23.95" W

Cored Interval: 1271 - 1336 ft.
387.5 - 407.3 m

K.B. Elev.: 593 ft. 180.8 m
Pet. Res. Core No.: #914

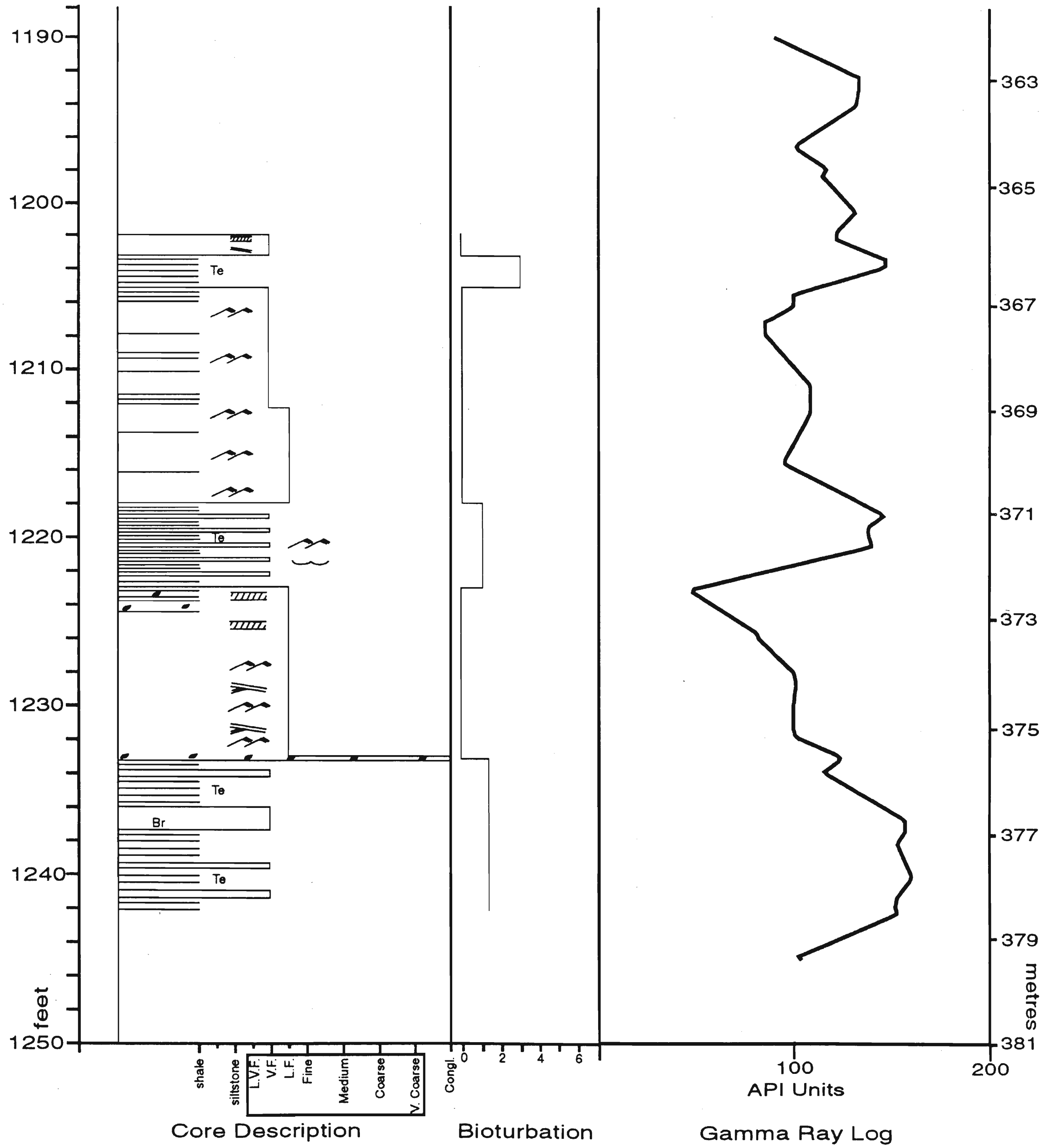


Well Name: CWP 68-5
Block Number: 63-G

Latitude: 42 38' 23.2" N
Longitude: 80 13' 25.5" W

Cored Interval: 1202 - 1242 ft.
366.4 - 378.6 m

K.B. Elev.: 599 ft. 182.6 m
Pet. Res. Core No.: #846

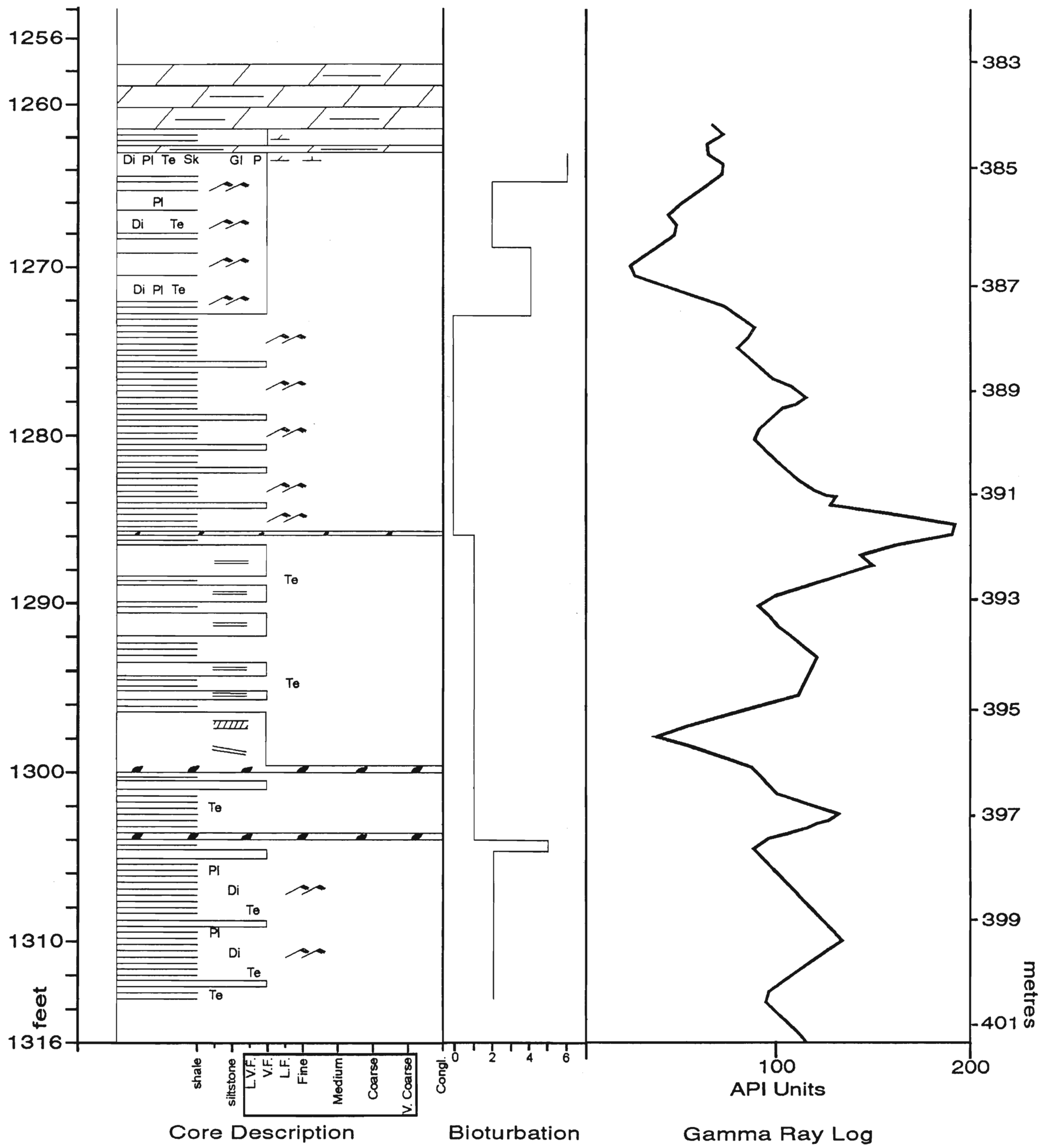


Well Name: Pembina #3 Lake Erie 64-S
Block Number: 64-S

Latitude: 42 36' 15.15" N
Longitude: 80 06' 45.15" W

Cored Interval: 1257 - 1313 ft.
383.3 - 400.3 m

K.B. Elev.: 592 ft. 180.4 m
Pet. Res. Core No.: #775

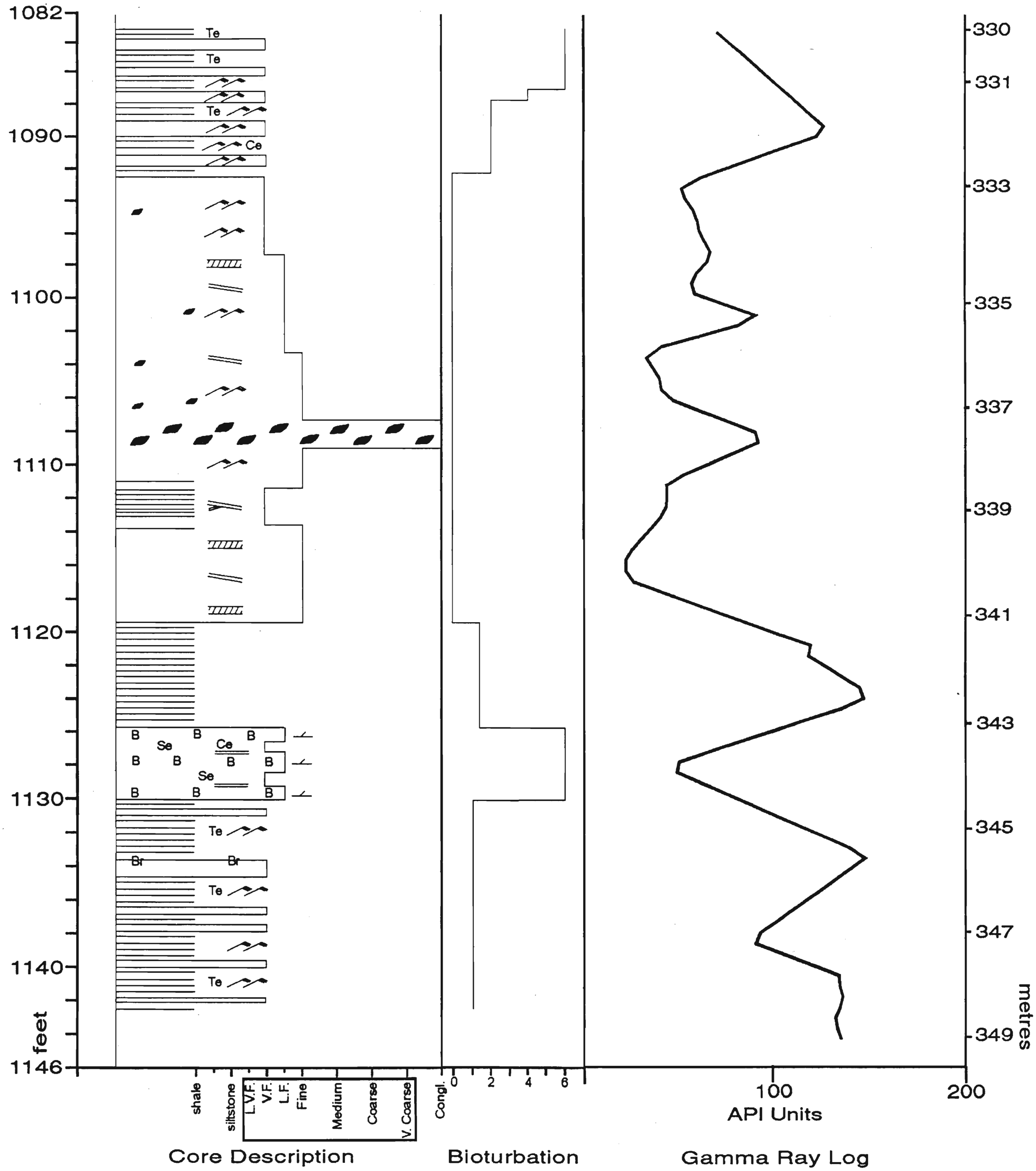


Well Name: Pembina #2 Lake Erie 65-E
Block Number: 65-E-2

Latitude: 42 39' 45.47" N
Longitude: 80 04' 44.99" W

Cored Interval: 1083 - 1143 ft.
330.0 - 348.3 m

K.B. Elev.: 593 ft. 180.7 m
Pet. Res. Core No.: #916

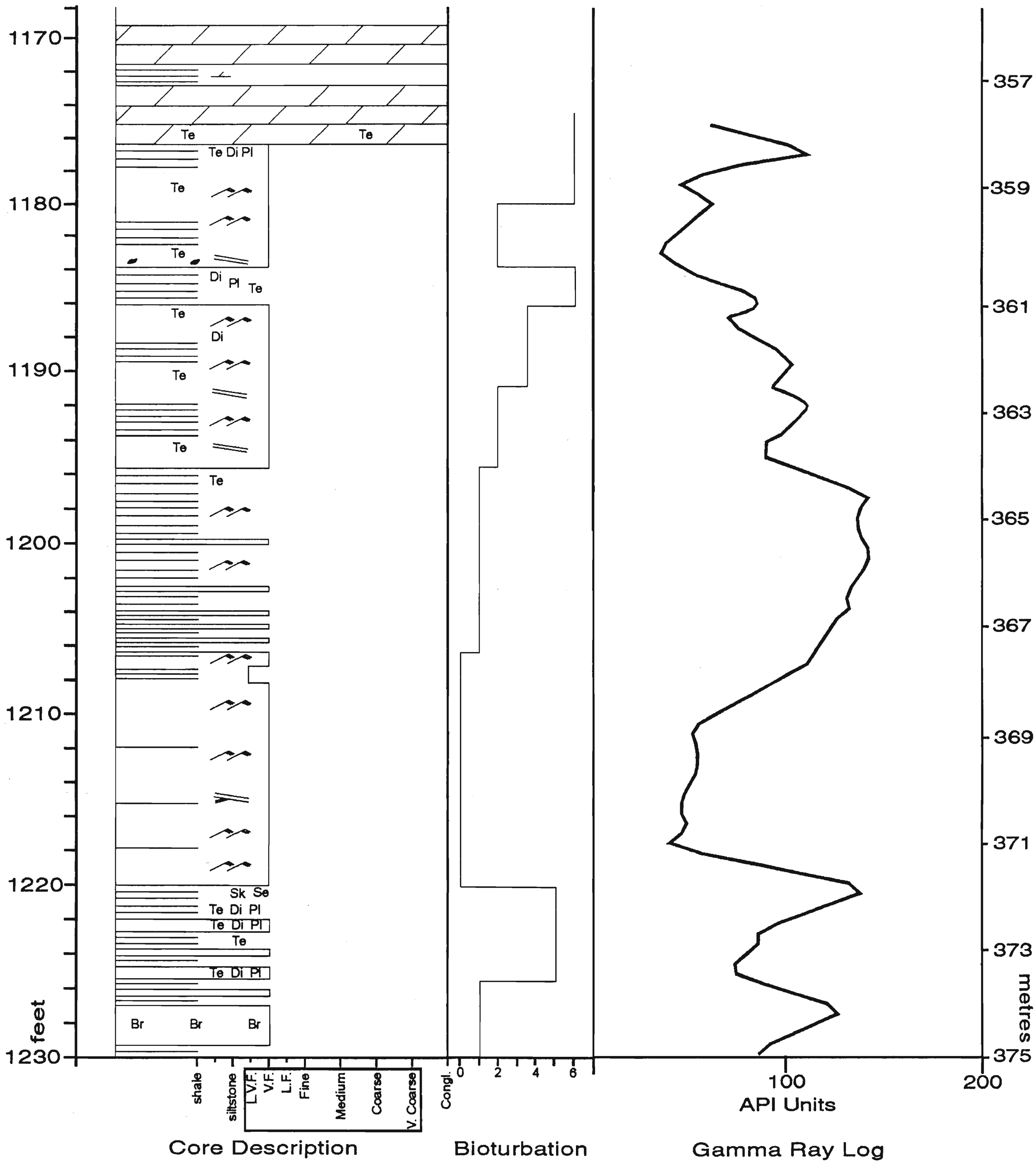


Well Name: Pembina #4 Lake Erie 67-F
Block Number: 67-F-4

Latitude: 42 38' 12.21" N
Longitude: 79 54' 16.36" W

Cored Interval: 1170 - 1230 ft.
356.5 - 374.7 m

K.B. Elev.: 592 ft. 180.5 m
Pet. Res. Core No.: #774

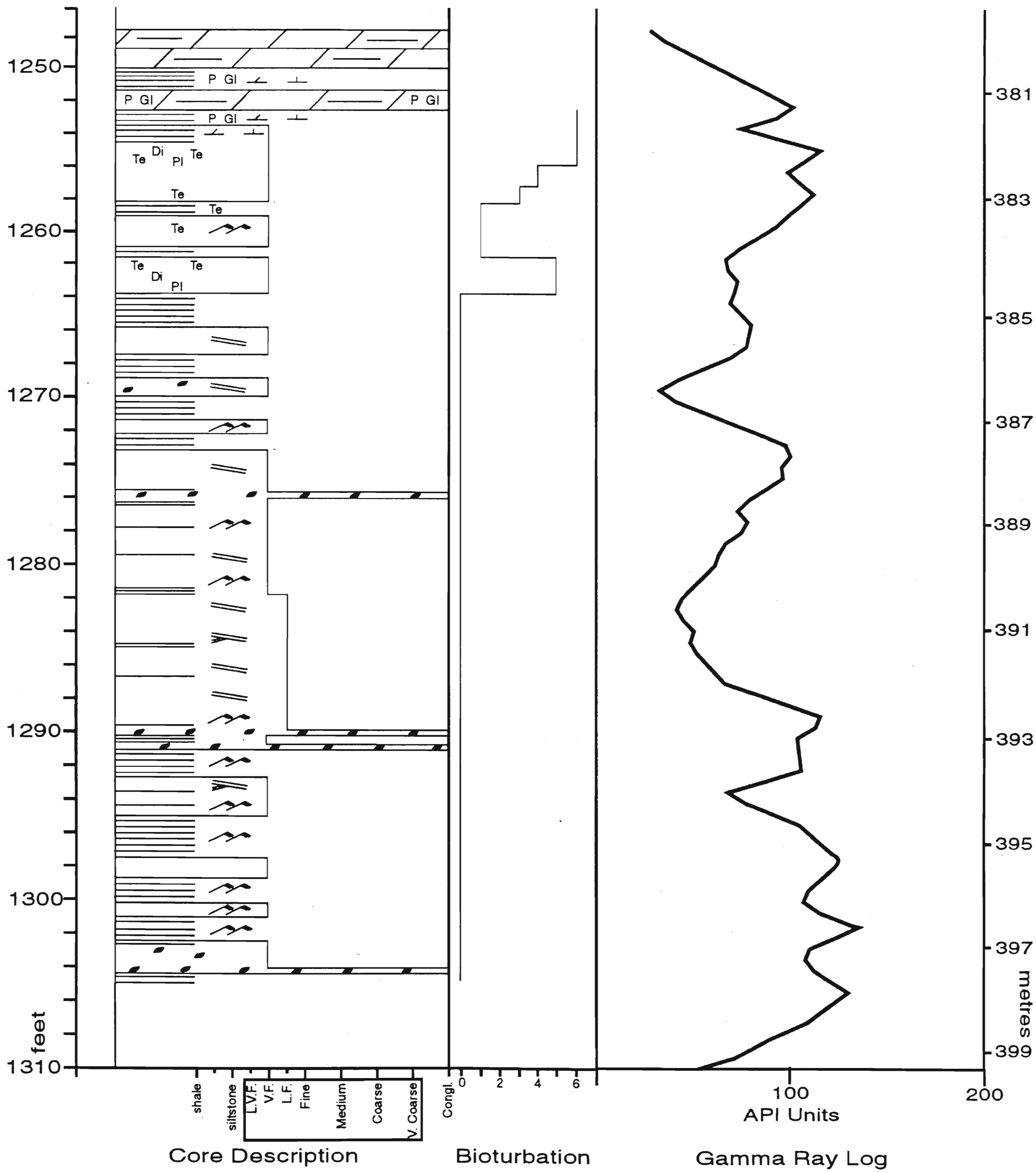


Well Name: Pembina #2A Lake Erie 68-Q
Block Number: 68-Q-2A

Latitude: 42 41' 21.98" N
Longitude: 80 33' 36.76" W

Cored Interval: 1247 - 1306 ft.
393.9 - 412.8 m

K.B. Elev.: 616 ft. 187.8 m
Pet. Res. Core No.: #919

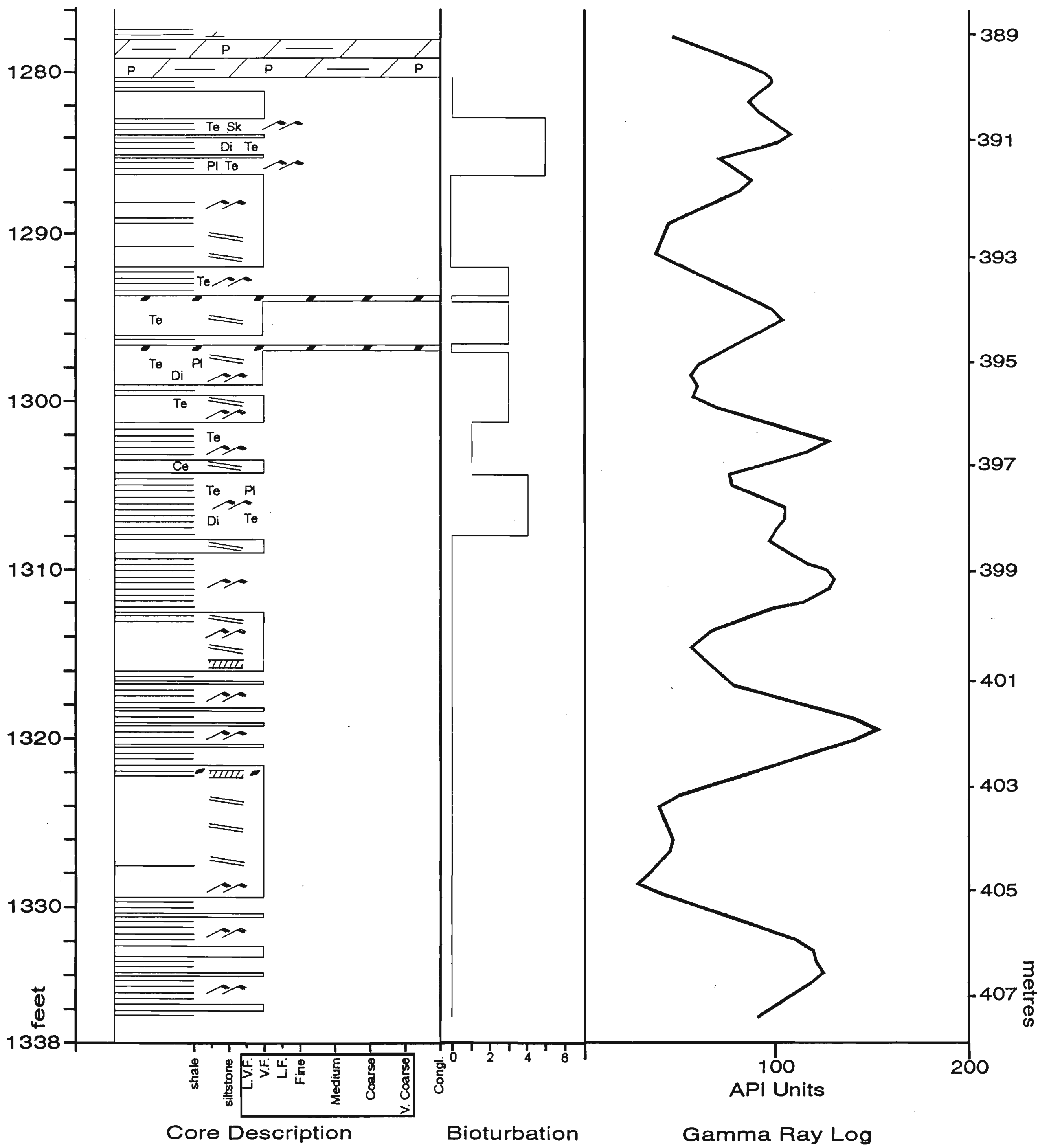


Well Name: Pembina #1 Lake Erie 69-Q
Block Number: 69-Q

Latitude: 42 36' 41.72" N
Longitude: 79 43' 16.27" W

Cored Interval: 1278 - 1338 ft.
389.5 - 407.8 m

K.B. Elev.: 593 ft. 180.7 m
Pet. Res. Core No.: #918



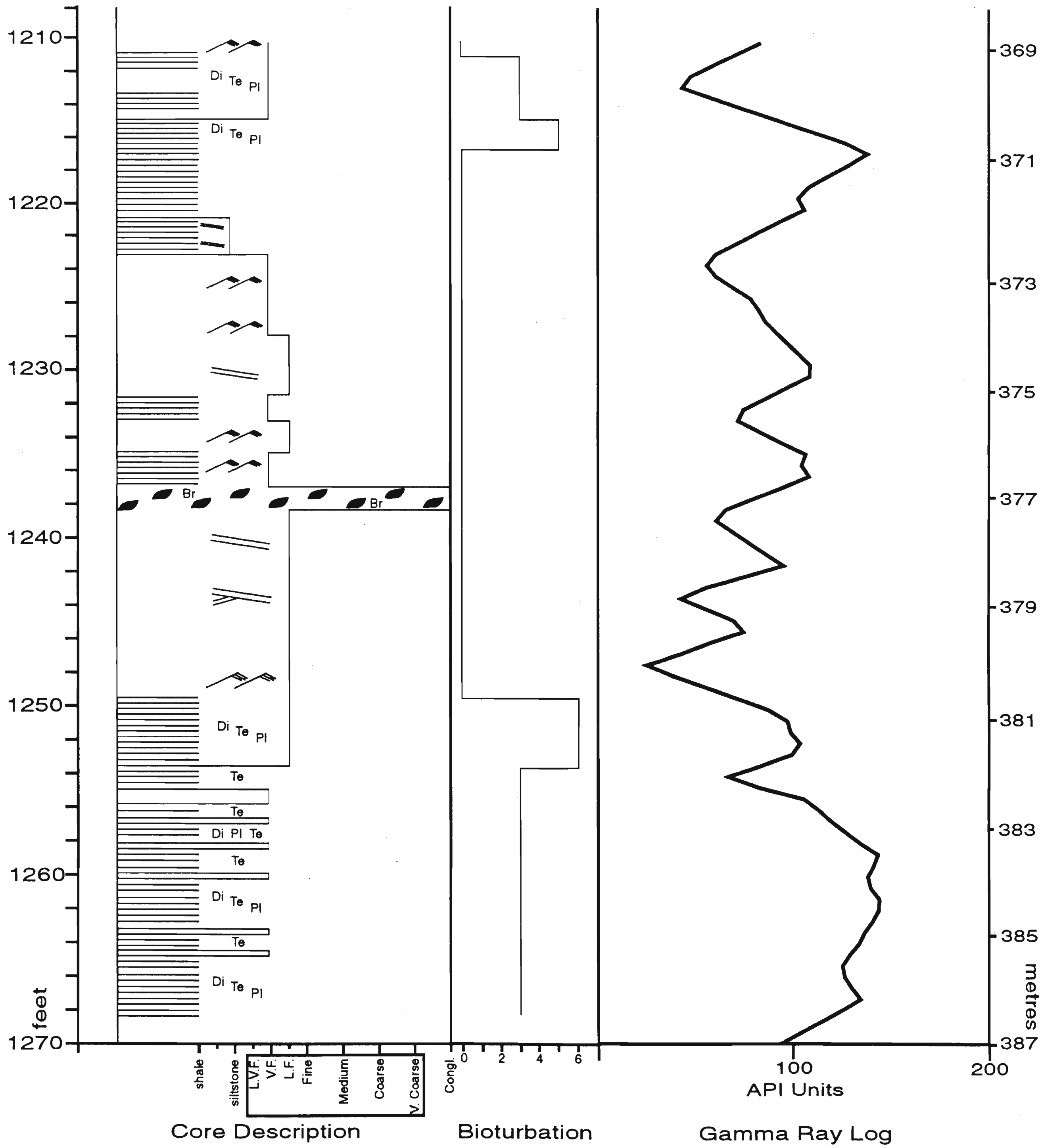
Well Name: Pembina #2 Lake Erie 70-G
Block Number: 70-G-2

Latitude: 42 38' 42.7" N
Longitude: 79 38' 42.8" W

Cored Interval: 1184 - 1269 ft.
360.8 - 386.6 m

K.B. Elev.: 593 ft. 180.6 m
Pet. Res. Core No.: #776

Page One Interval: 369.0 - 386.6



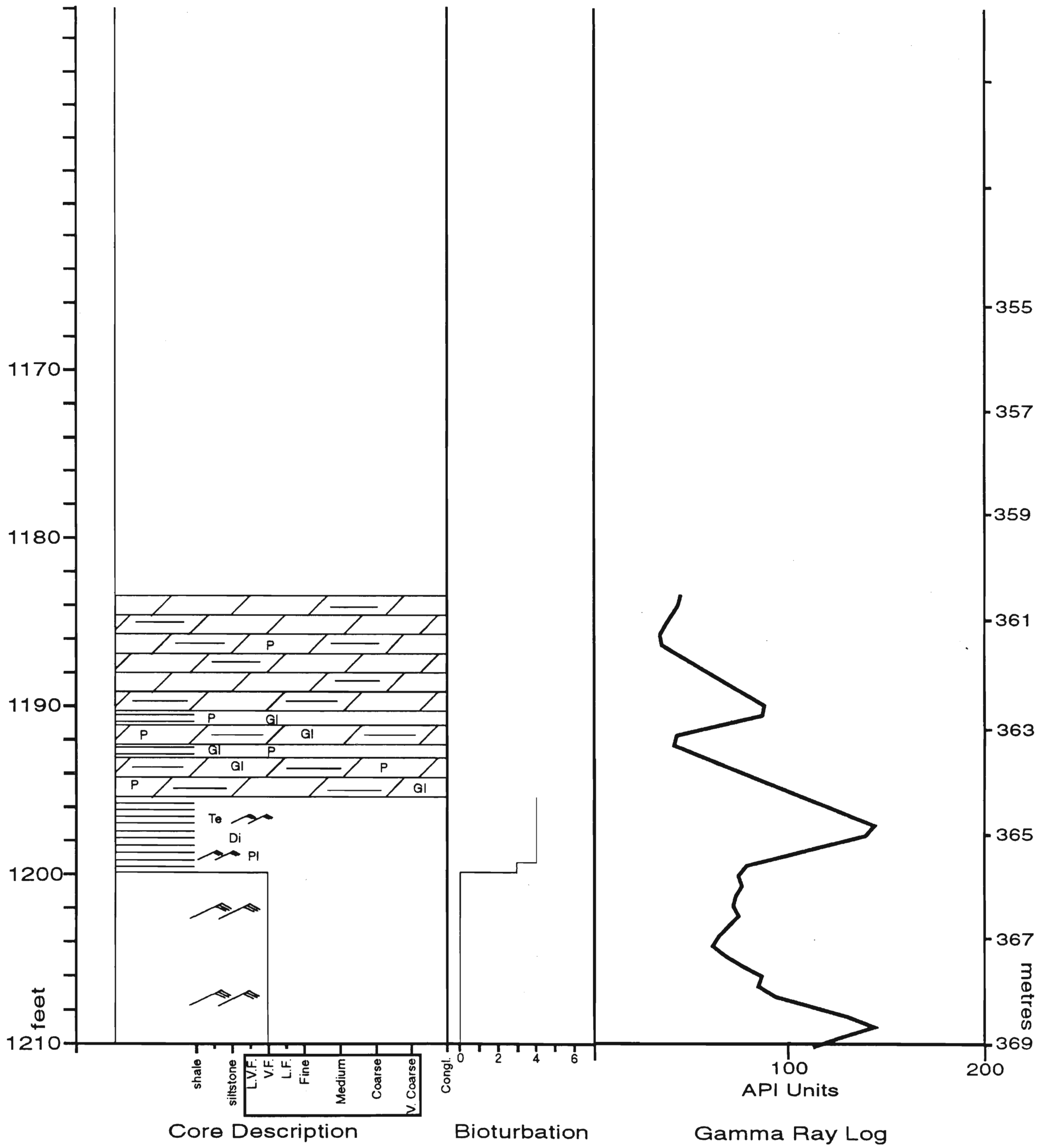
Well Name: Pembina #2 Lake Erie 70-G
Block Number: 70-G-2

Latitude: 42 38' 42.7" N
Longitude: 79 38' 42.8" W

Cored Interval: 1184 - 1269 ft.
360.8 - 386.6 m

K.B. Elev.: 593 ft. 180.6 m
Pet. Res. Core No.: #776

Page #2 Interval: 369.0 - 360.8 m

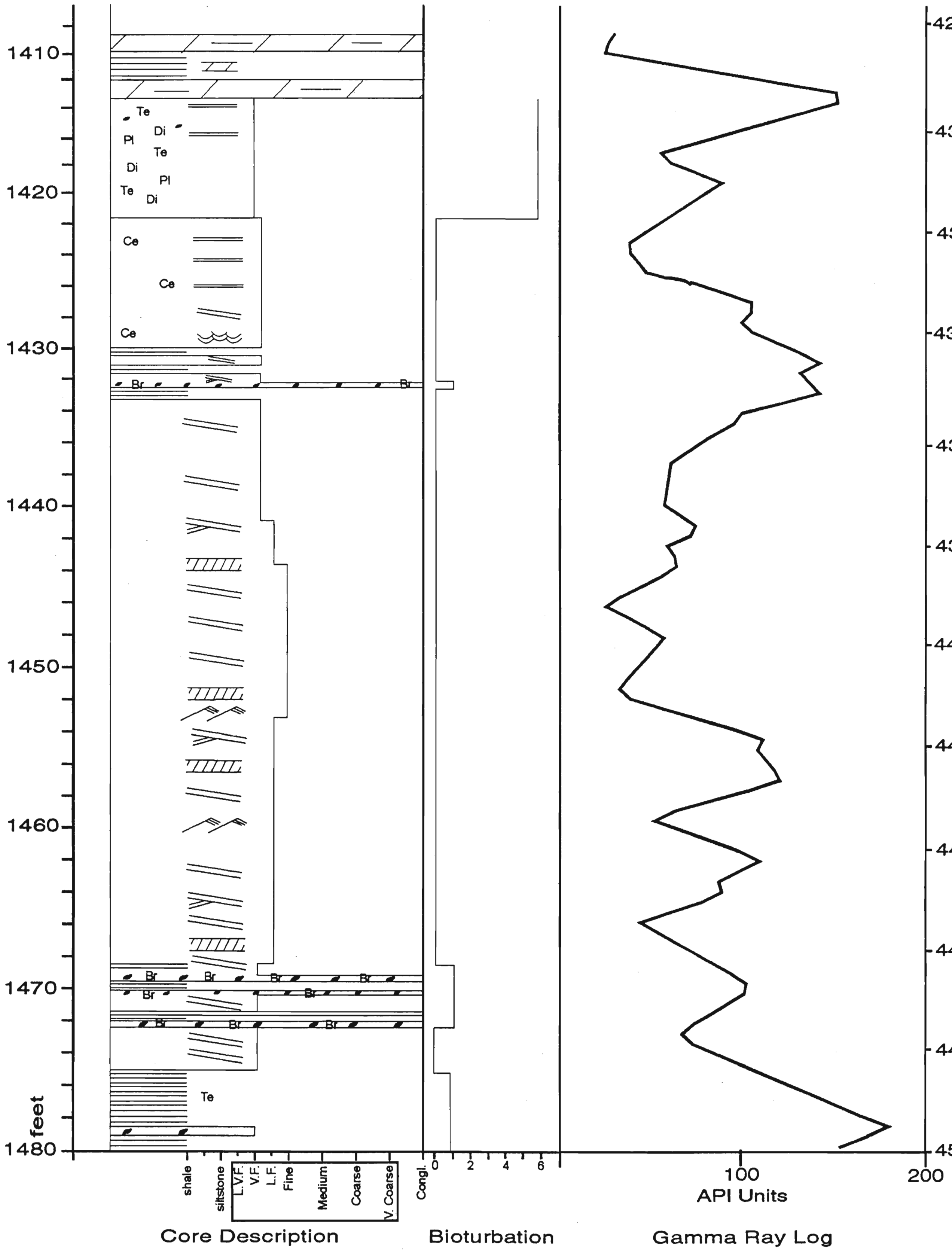


Well Name: Pembina Lake Erie 89-K-4
Block Number: 89-K

Latitude: 42 32' 13.55" N
Longitude: 80 00' 13.84" W

Cored Interval: 1417 - 1489 ft.
429.3 - 451.0 m

K.B. Elev.: 593 ft. 180.8 m
Pet. Res. Core No.: #870

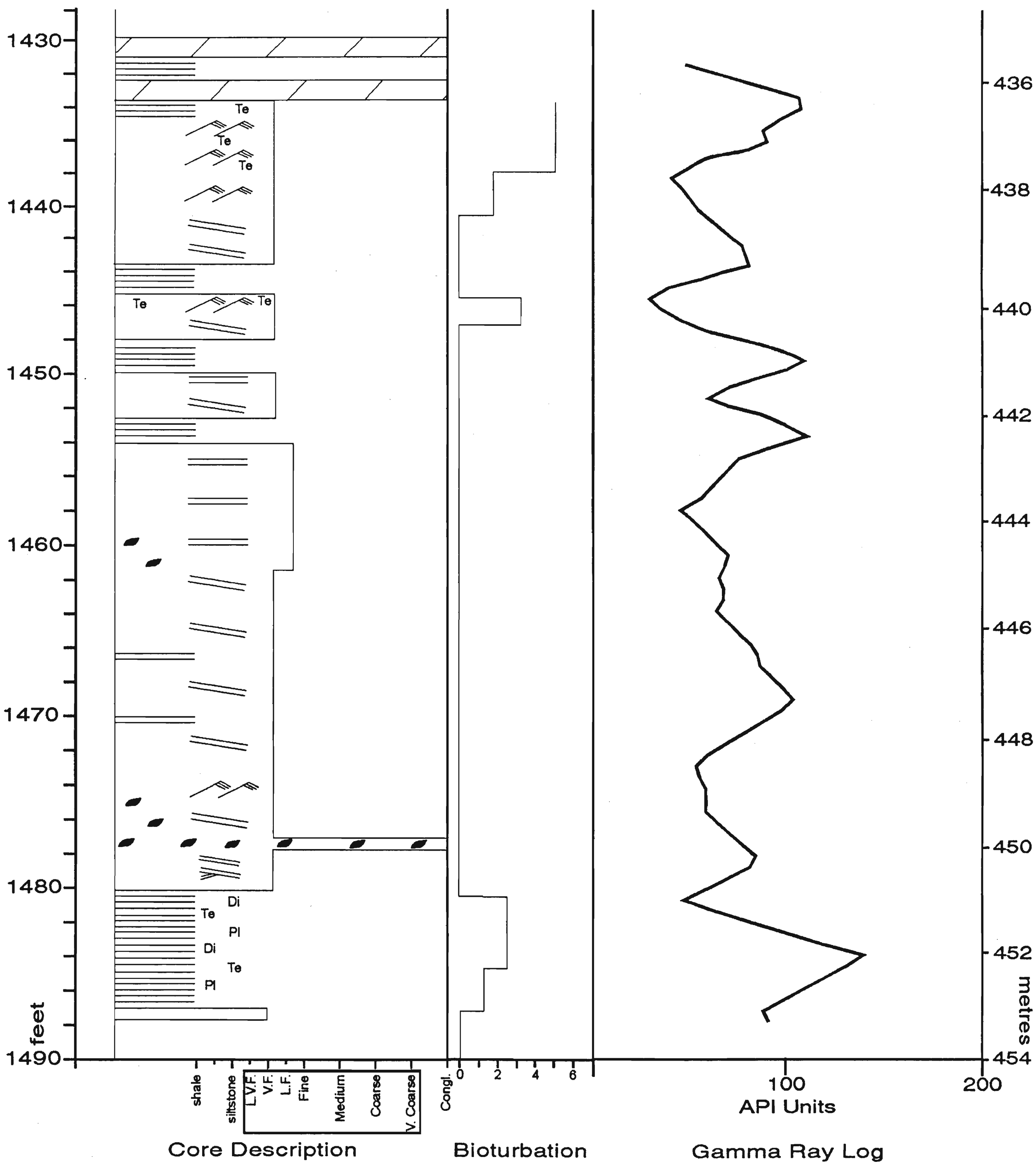


Well Name: Pembina Lake Erie 91-S-4
Block Number: 91-S

Latitude: 42 31' 14.08" N
Longitude: 80 11' 16.52" W

Cored Interval: 1429 - 1488 ft.
435.5 - 453.4 m

K.B. Elev.: 593 ft. 180.7 m
Pet. Res. Core No.: #868

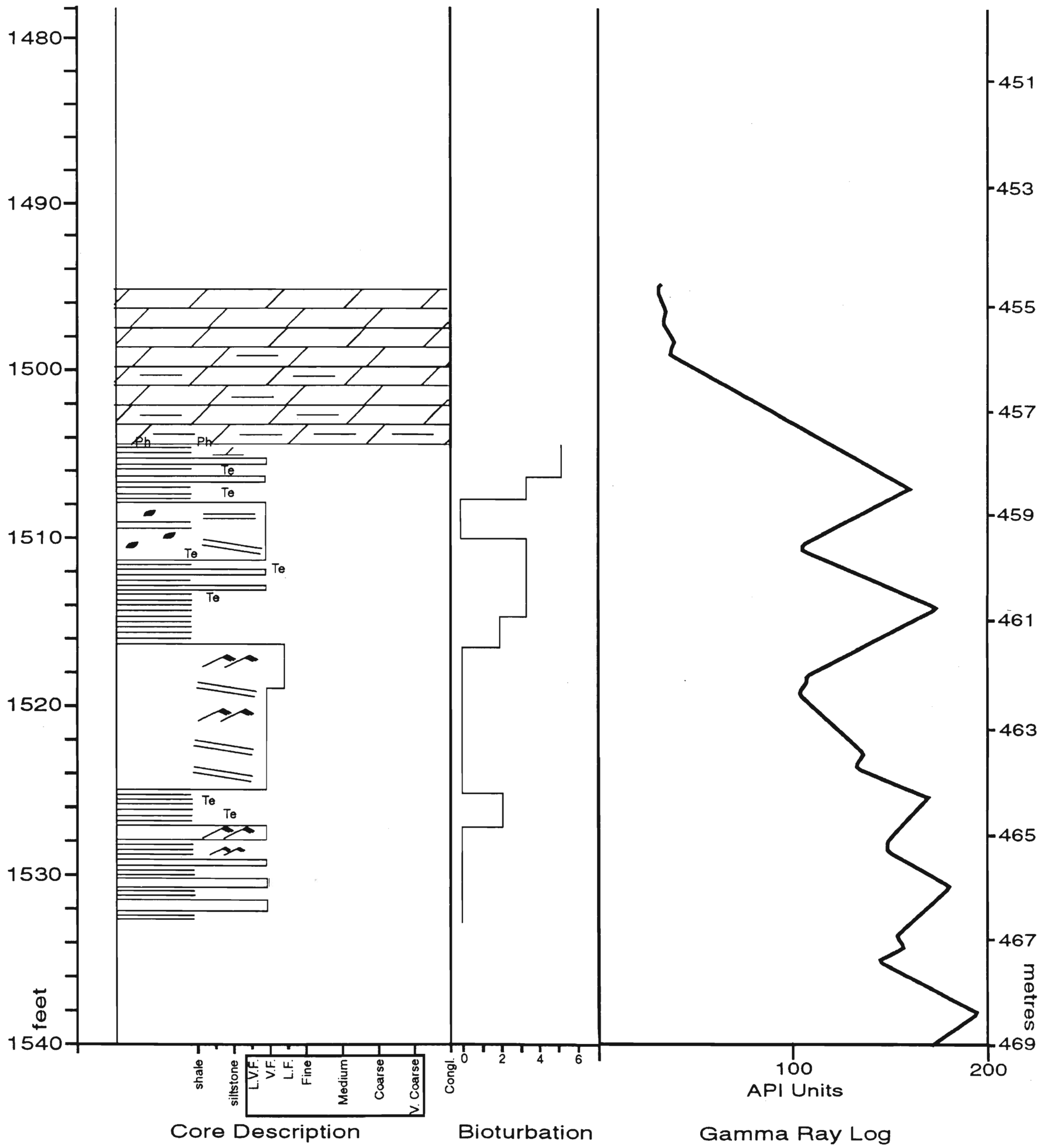


Well Name: Consumers Pan Am 13047
Block Number: 93-W

Latitude: 42 30' 54.7" N
Longitude: 80 22' 25.6" W

Cored Interval: 1495 - 1535 ft.
455.7 - 467.9 m

K.B. Elev.: 617 ft. 188.1 m
Pet. Res. Core No.: #822

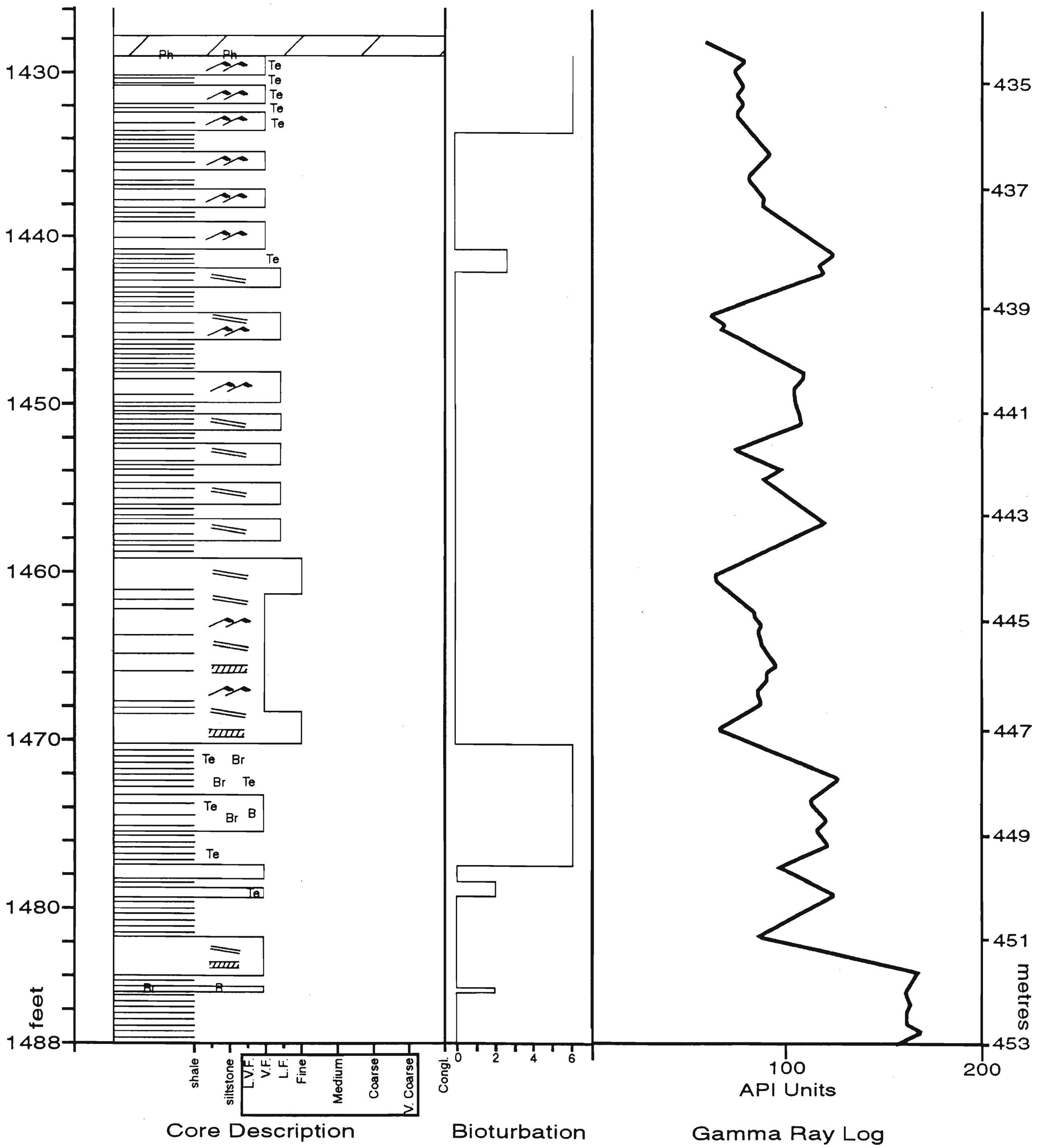


Well Name: Consumers 13300
Block Number: 94-K

Latitude: 42 32' 29.18" N
Longitude: 80 25' 48.33" W

Cored Interval: 1428 - 1488 ft.
435.5 - 453.5 m

K.B. Elev.: 620 ft. 189.0 m
Pet. Res. Core No.: #360

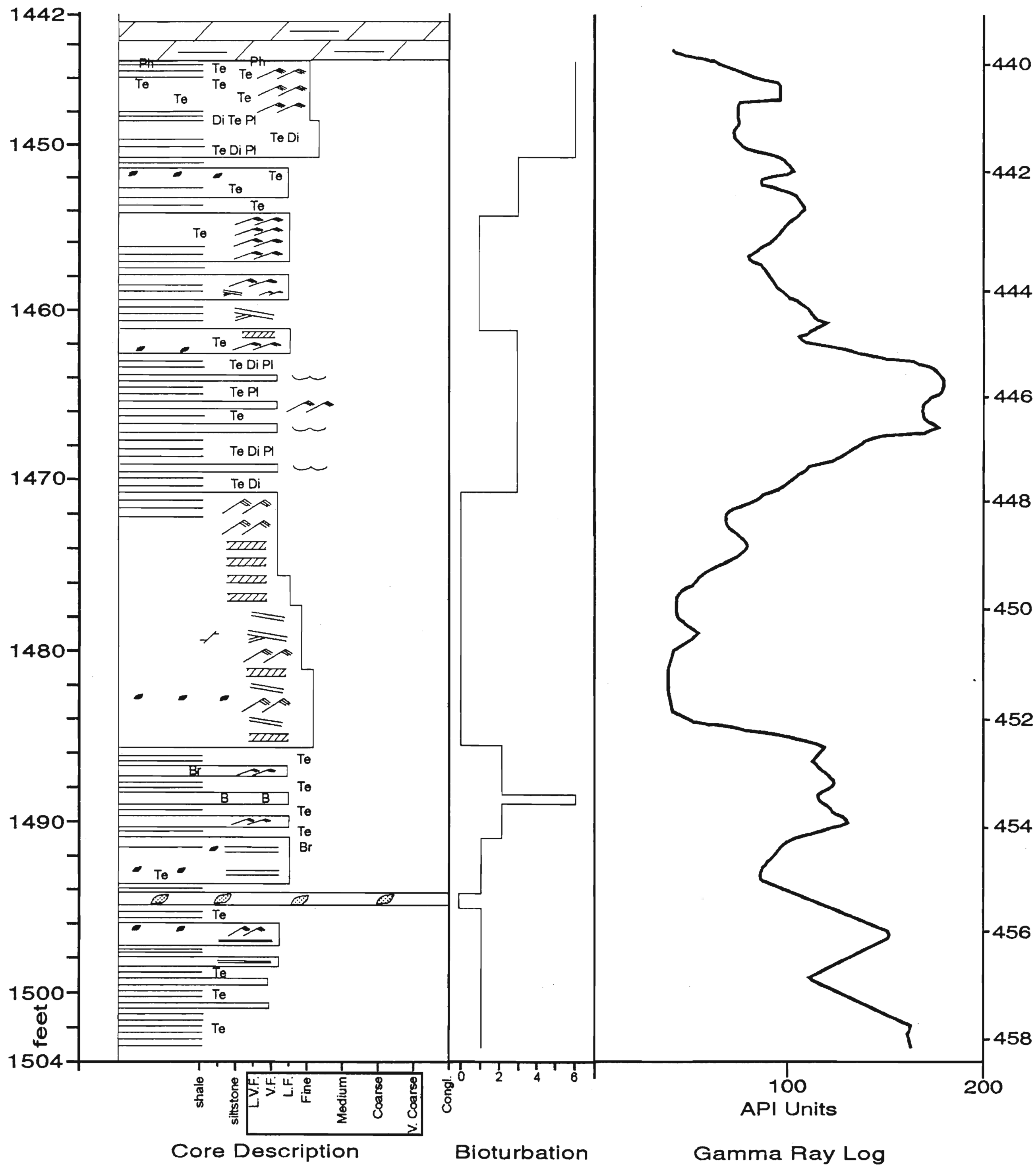


Well Name: Consumers 13170
Block Number: 94-M

Latitude: 42 32' 16.18" N
Longitude: 80 27' 34.75" W

Cored Interval: 1443 - 1503 ft.
439.8 - 458.1 m

K.B. Elev.: 616 ft. 187.8 m
Pet. Res. Core No.: #438

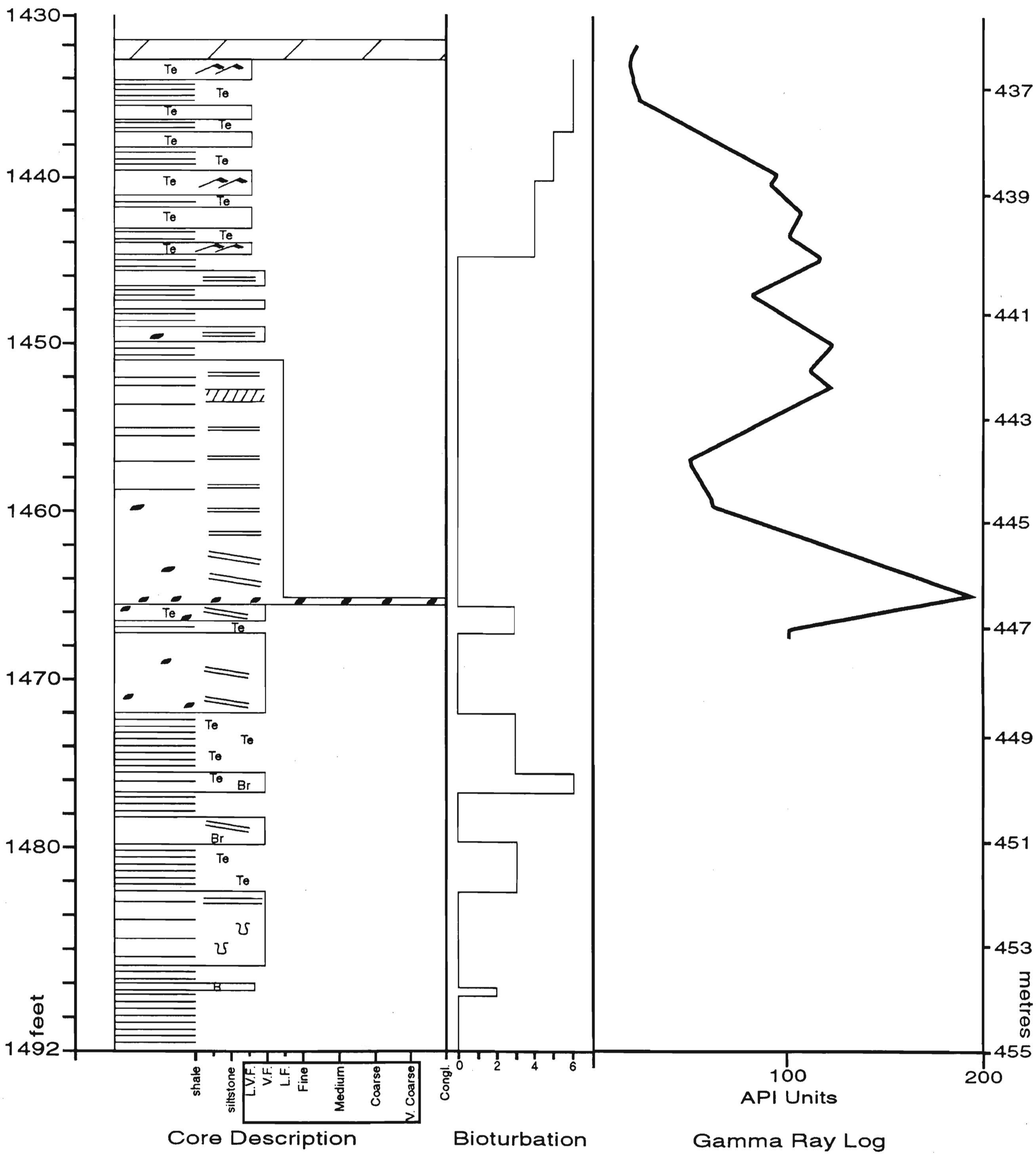


Well Name: Consumers 13321
Block Number: 95-K

Latitude: 42 32' 03.13" N
Longitude: 80 30' 09.60" W

Cored Interval: 1432 - 1492 ft.
436.5 - 454.3 m

K.B. Elev.: 597 ft. 182.0 m
Pet. Res. Core No.: #662

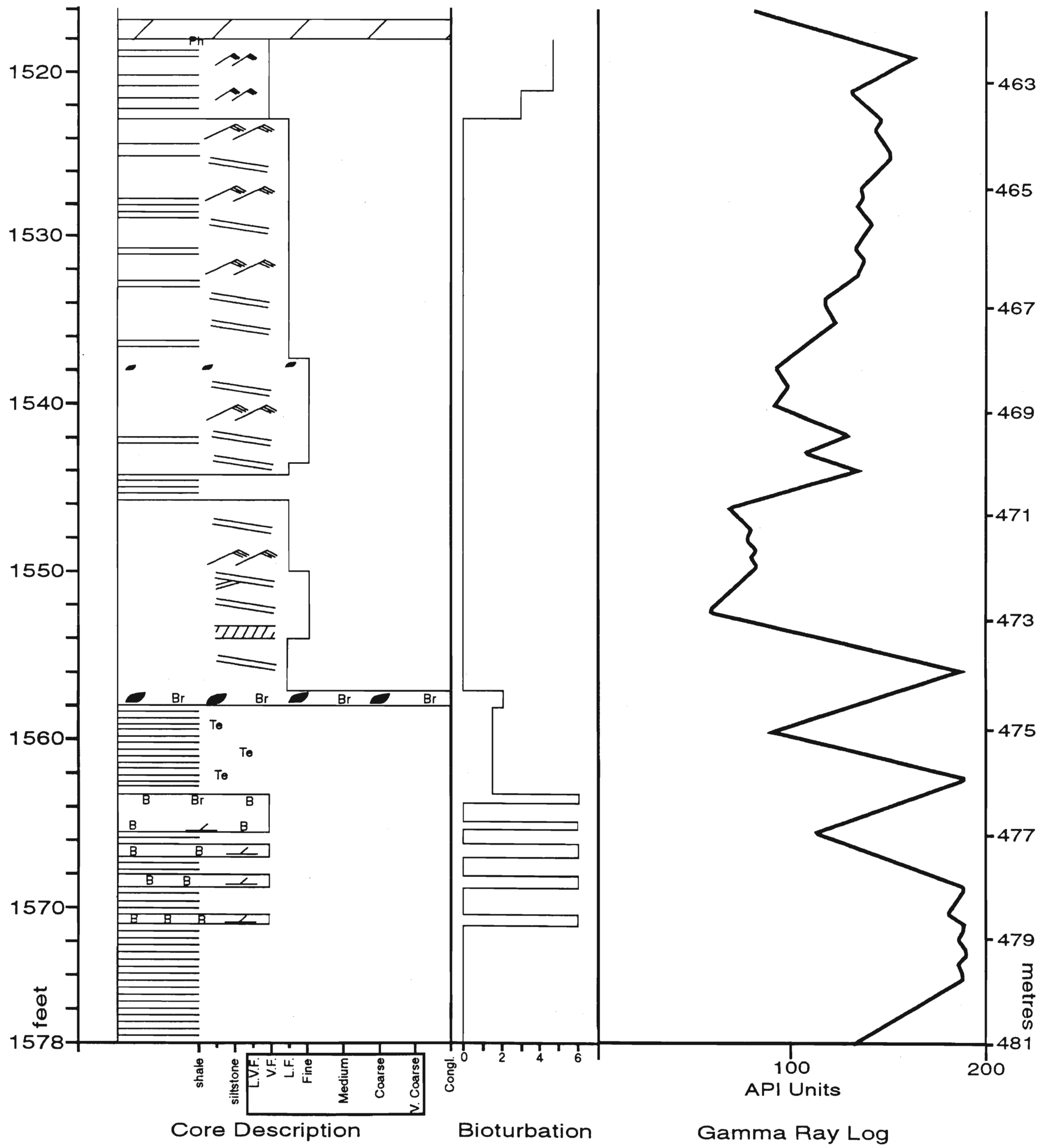


Well Name: Consumers 13148
Block Number: 96-V

Latitude: 42 30' 43.05" N
Longitude: 80 36' 32.39" W

Cored Interval: 1517 - 1577 ft.
462.4 - 480.7 m

K.B. Elev.: 616 ft. 187.8 m
Pet. Res. Core No.: #341

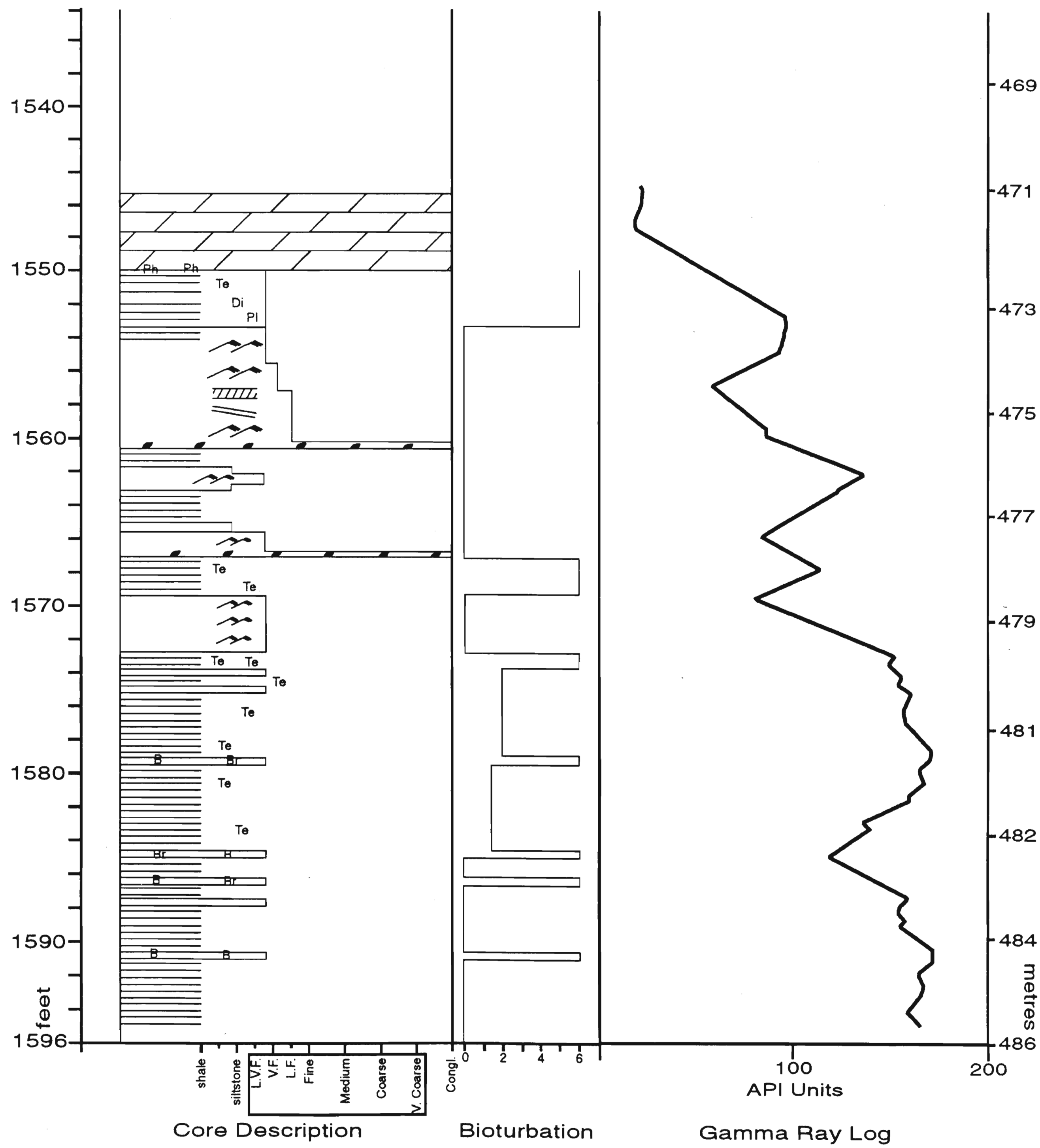


Well Name: Consumers 13059
Block Number: 97-P

Latitude: 42 31' 00.30" N
Longitude: 80 44' 59.00" W

Cored Interval: 1545 - 1595 ft.
470.9 - 485.7 m

K.B. Elev.: 615 ft 187.5 m
Pet. Res. Core No.: #833

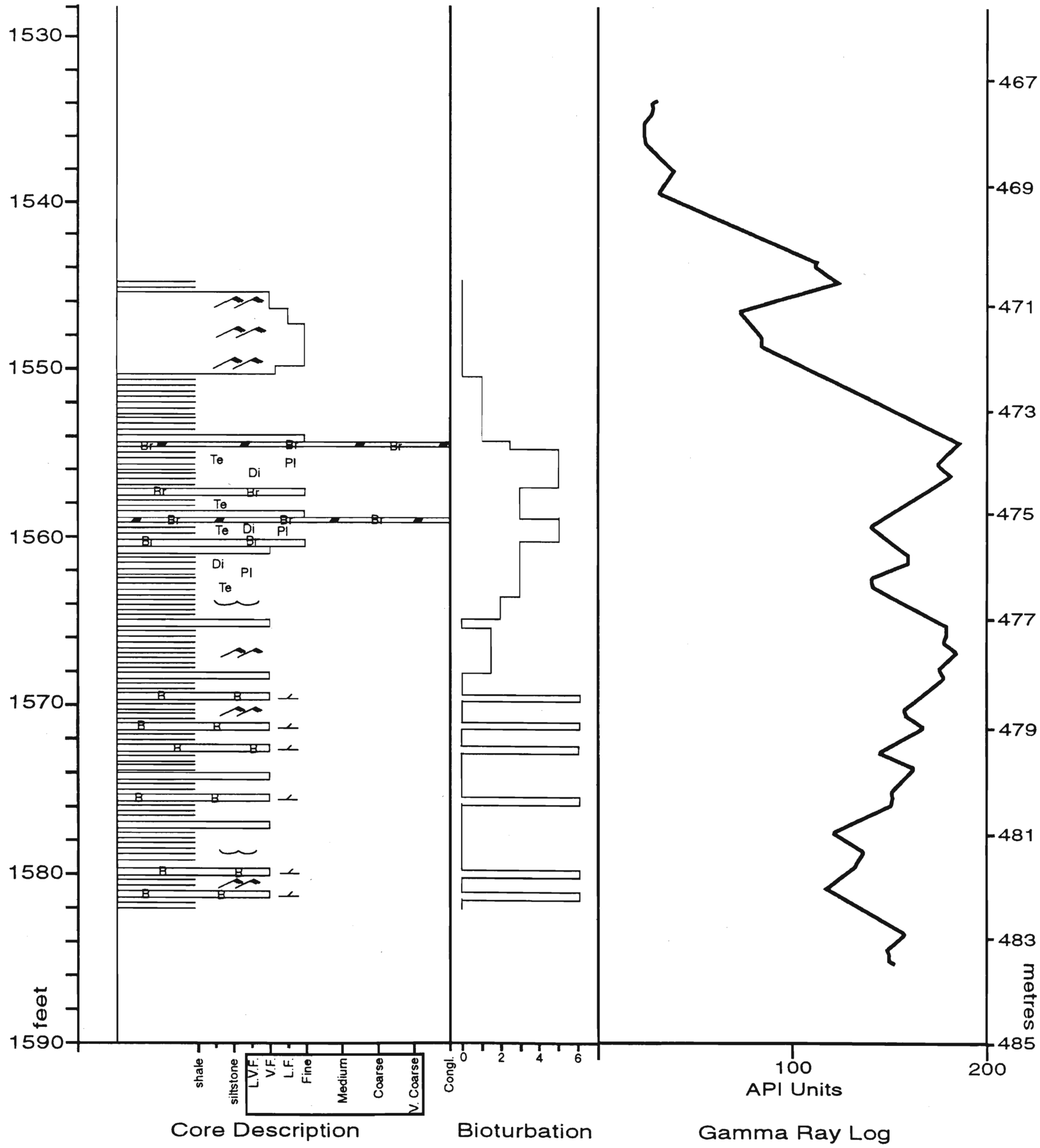


Well Name: Consumers 13081
Block Number: 98-P

Latitude: 42 31' 40.20" N
Longitude: 80 49' 10.27" W

Cored Interval: 1545 - 1590 ft. (lost 1582-90)
470.9 - 484.6 m

K.B. Elev.: 614 ft. 187.1 m
Pet. Res. Core No.: #332

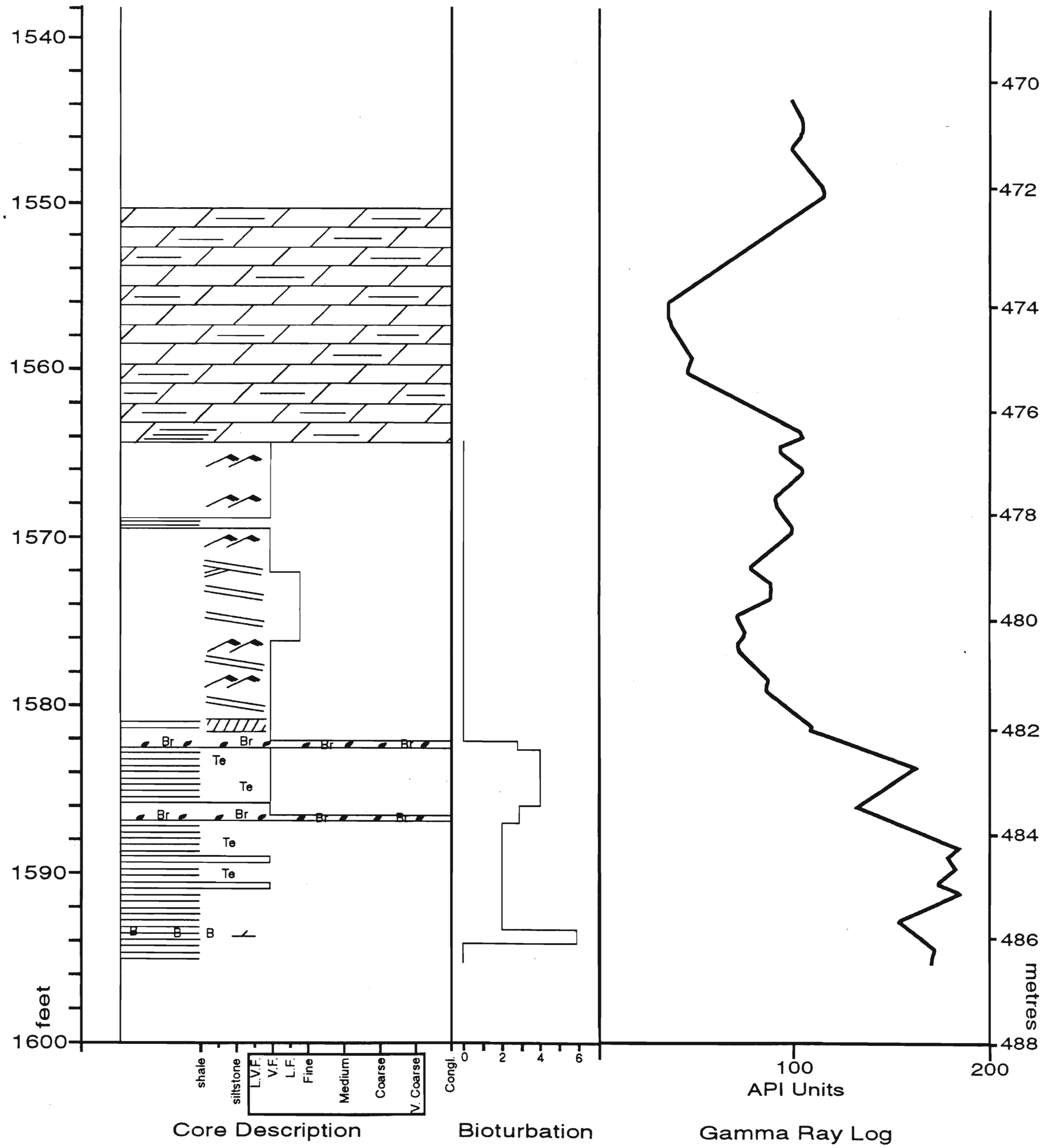


Well Name: Consumers 13067
Block Number: 98-Y

Latitude: 42 30' 59.10" N
Longitude: 80 49' 59.50" W

Cored Interval: 1550 - 1599 ft. (lost 1595-99')
472.4 - 487.4 m

K.B. Elev.: 615 ft. 187.5 m
Pet. Res. Core No.: #813

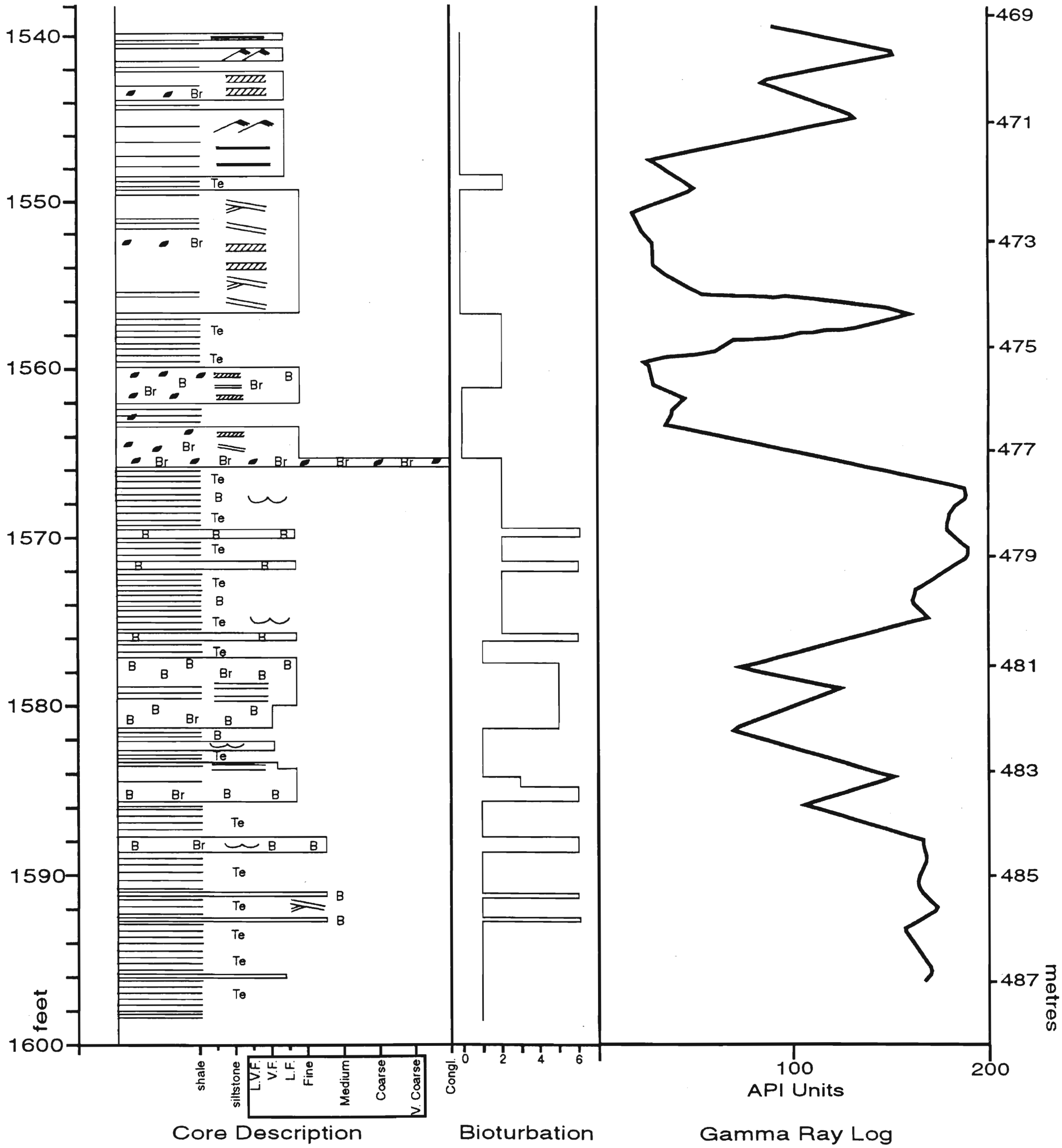


Well Name: Consumers 13169
Block Number: 99-K

Latitude: 42 32' 10.48" N
Longitude: 80 50' 48.52" W

Cored Interval: 1540 - 1597 ft.
469.4 - 486.8 m

K.B. Elev.: 616 ft. 187.8 m
Pet. Res. Core No.: #345

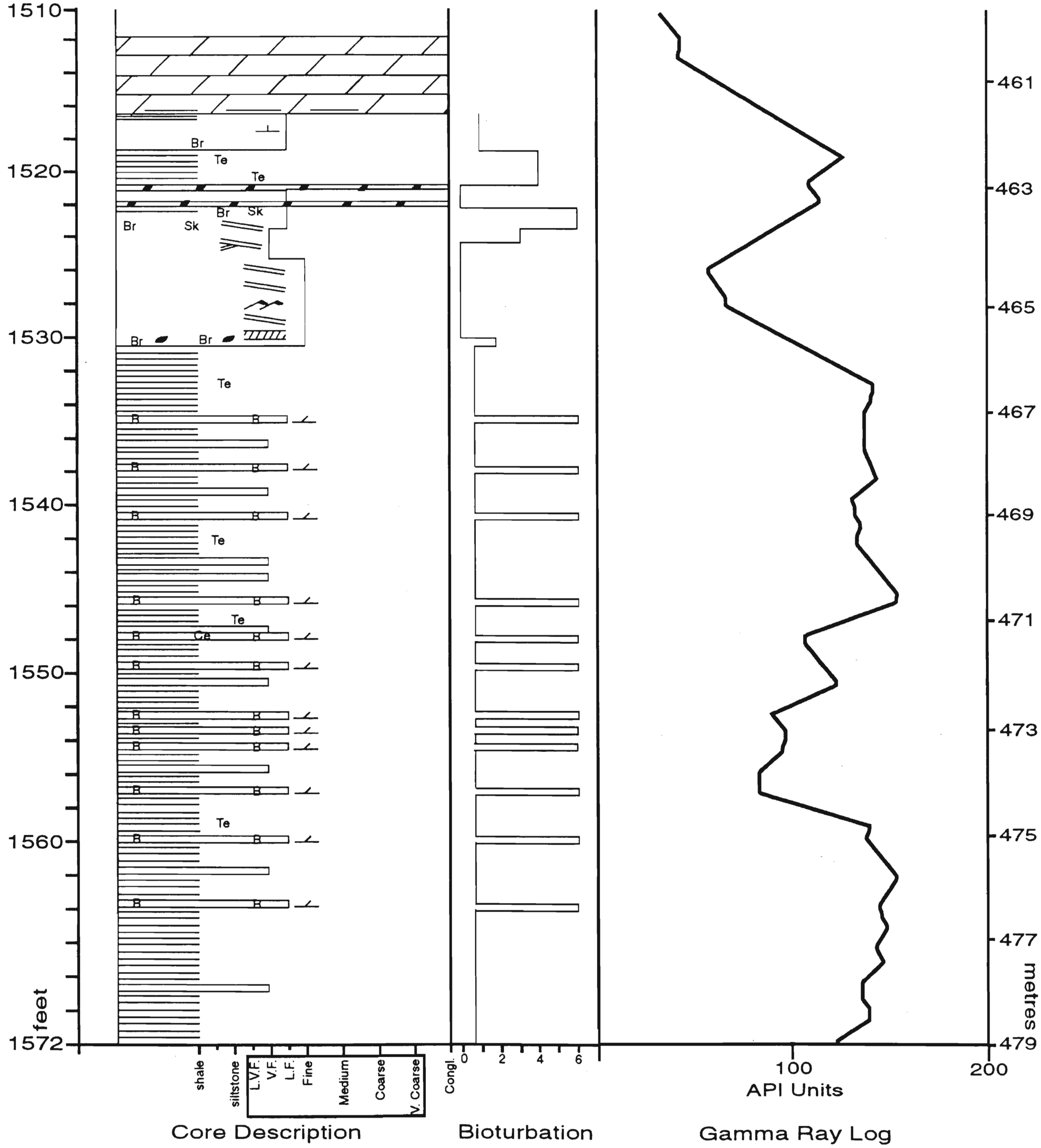


Well Name: Consumers 13034
Block Number: 100-I

Latitude: 42 33' 58.90" N
Longitude: 80 56' 53.50" W

Cored Interval: 1512 - 1572 ft.
460.9 - 479.1 m

K.B. Elev.: 616 ft. 187.8 m
Pet. Res. Core No.: #824

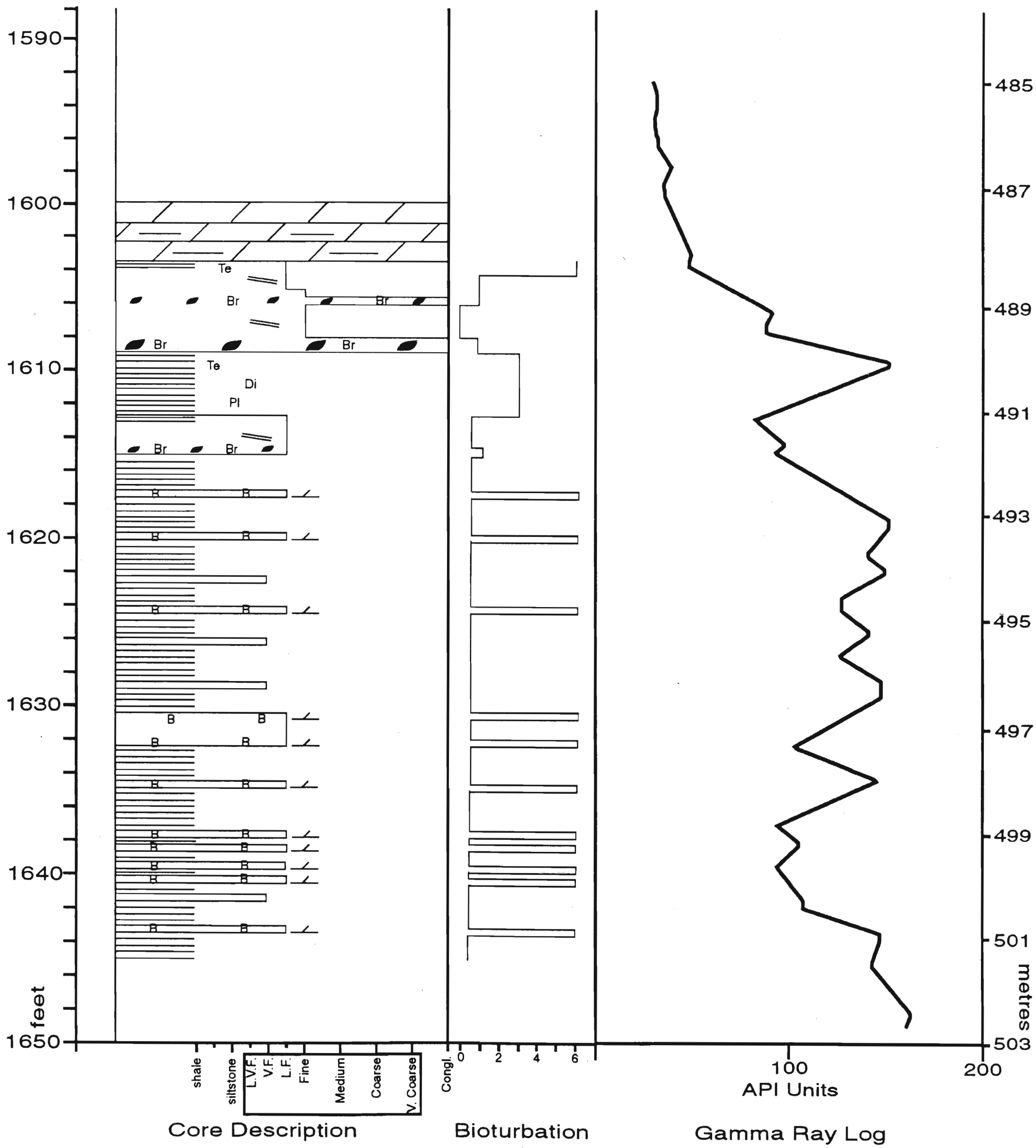


Well Name: Consumers 13035
Block Number: 101-K

Latitude: 42 32' 02.2" N
Longitude: 81 00' 34.0" W

Cored Interval: 1600 - 1645 ft.
487.7 - 501.4 m

K.B. Elev.: 615 ft. 187.5 m
Pet. Res. Core No.: #834

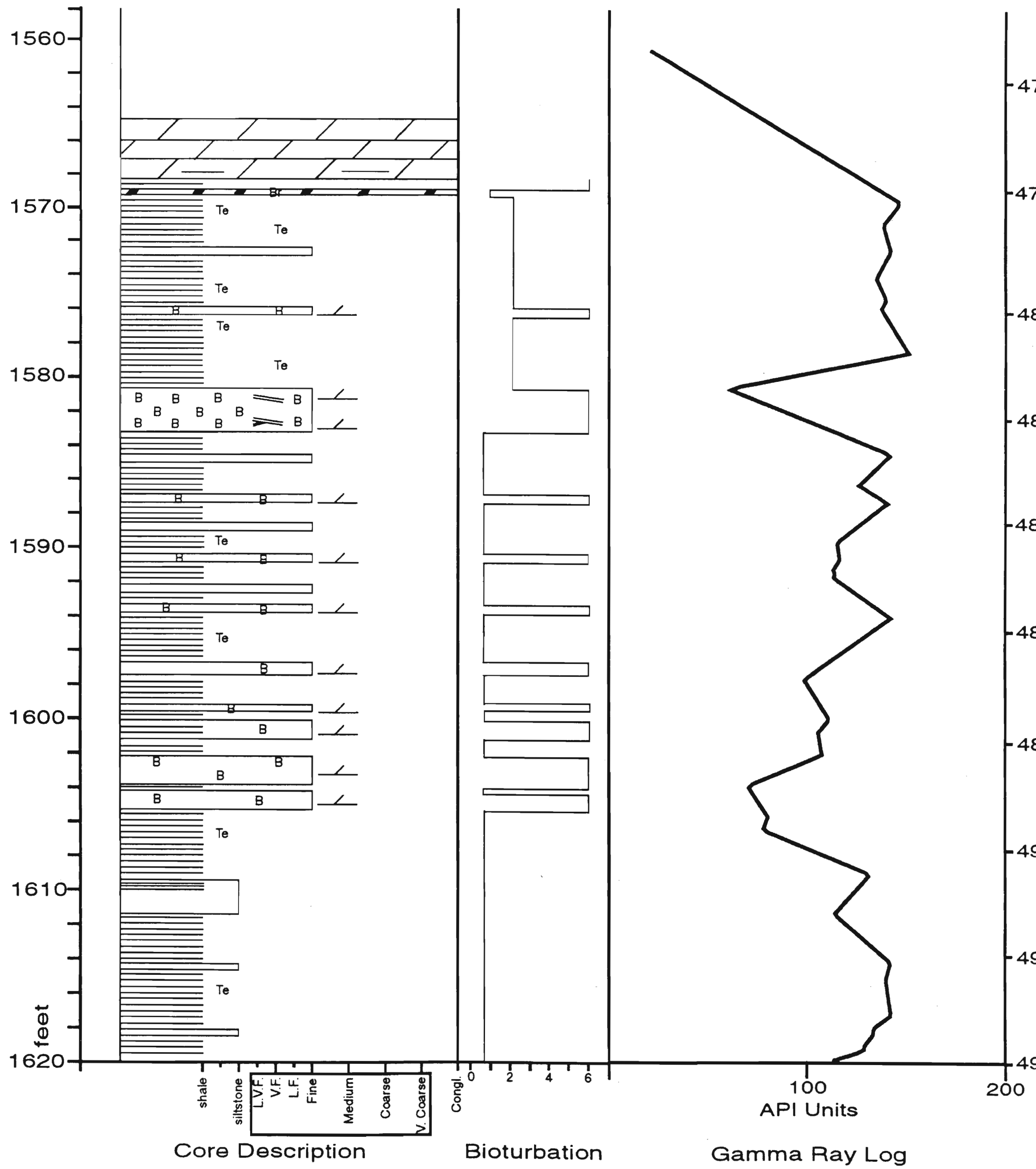


Well Name: Consumers 13038
Block Number: 102-B

Latitude: 42 34' 55.5" N
Longitude: 81 06' 06.6" W

Cored Interval: 1560 - 1620 ft. (1560-65 lost)
475.5 - 493.8 m

K.B. Elev.: 616 ft. 187.8 m
Pet. Res. Core No.: #805

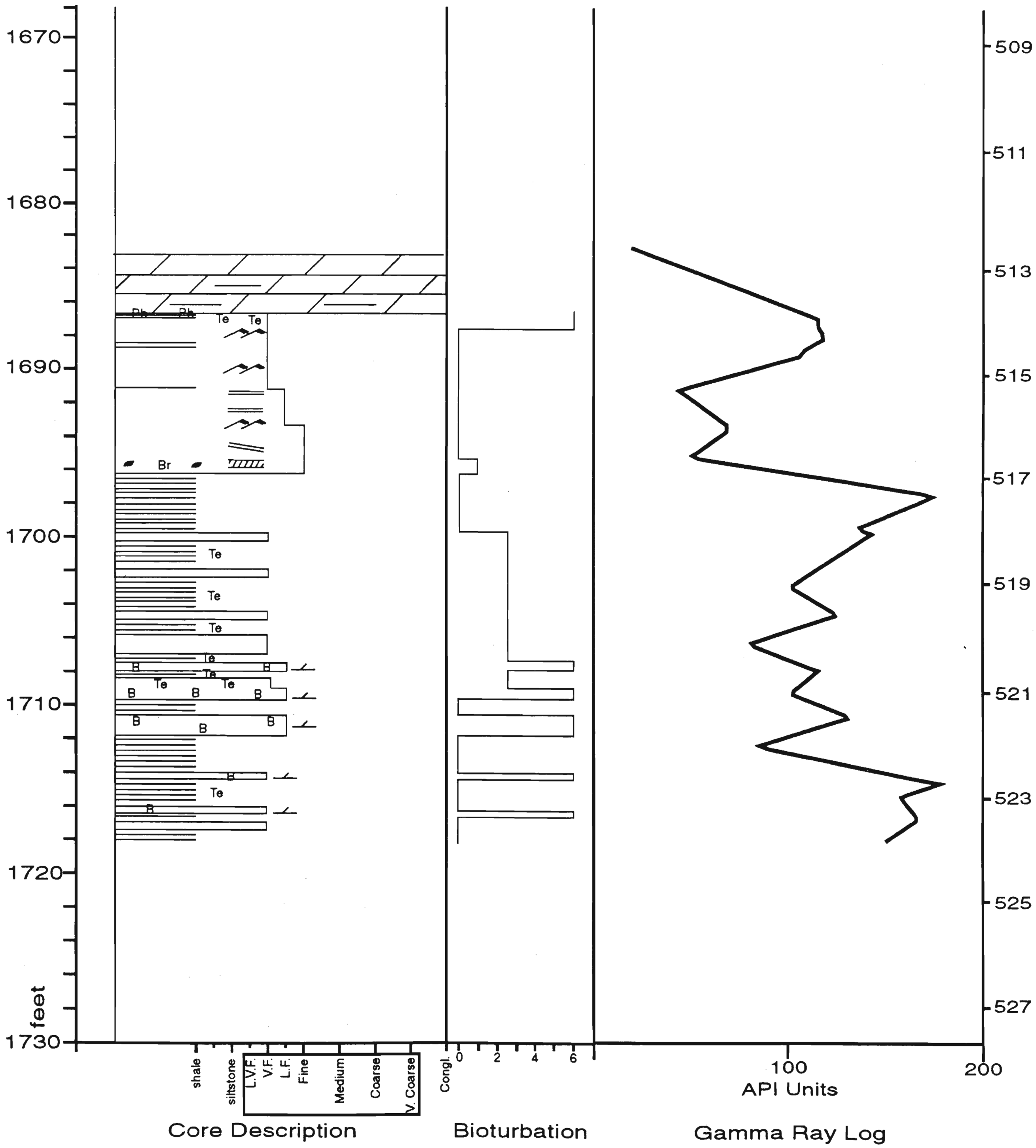


Well Name: Consumers 13036
Block Number: 118-M

Latitude: 42 27' 56.1" N
Longitude: 81 02' 33.5" W

Cored Interval: 1685 - 1720 ft. (1718-20 lost)
513.6 - 524.3 m

K.B. Elev.: 601 ft. 183.2 m
Pet. Res. Core No.: #808

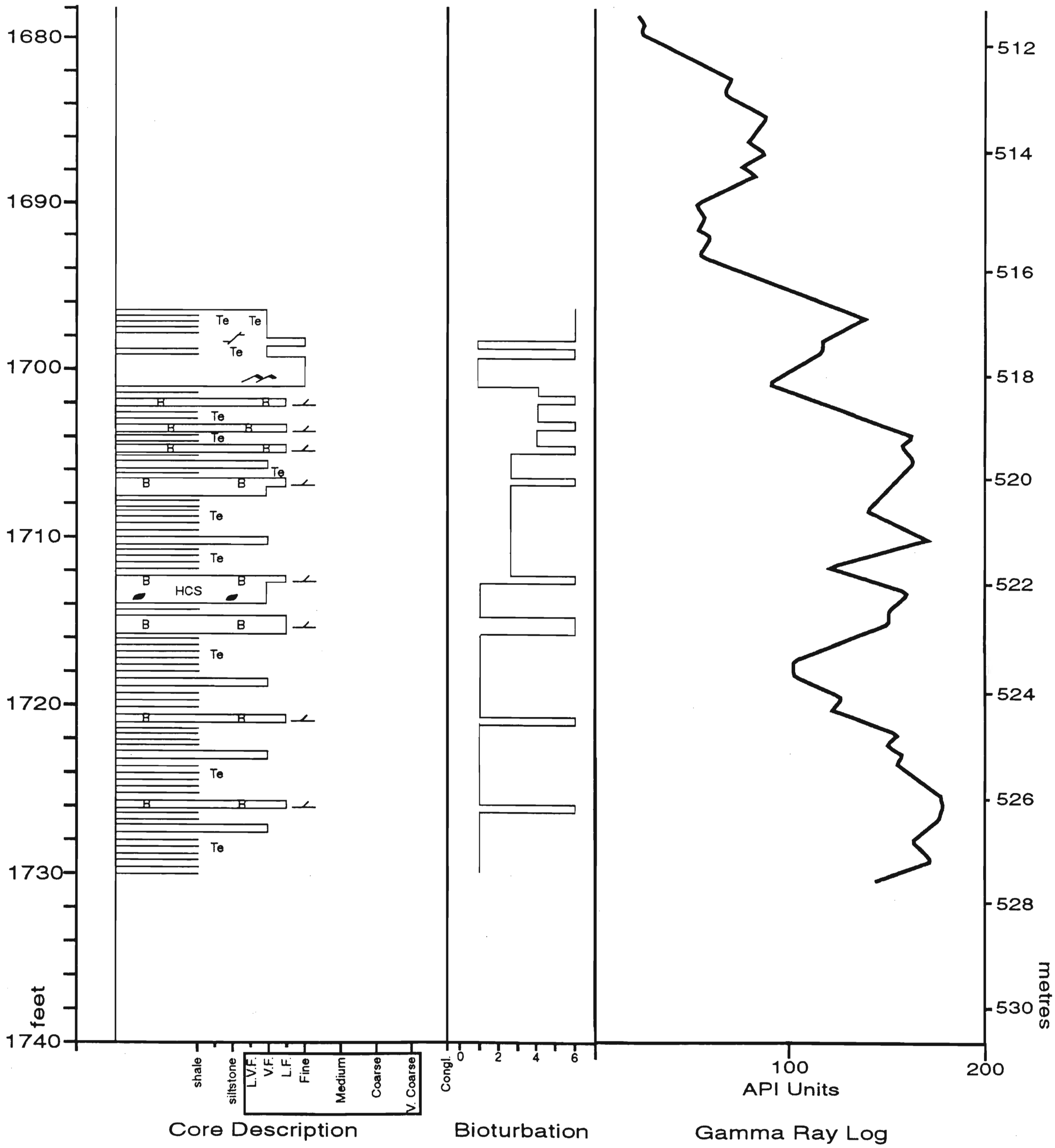


Well Name: Consumers 13053
Block Number: 119-A

Latitude: 42 29' 00.5" N
Longitude: 80 55' 39.0" W

Cored Interval: 1696 - 1730 ft.
517.0 - 527.3 m

K.B. Elev.: 616 ft. 187.8 m
Pet. Res. Core No.: #855

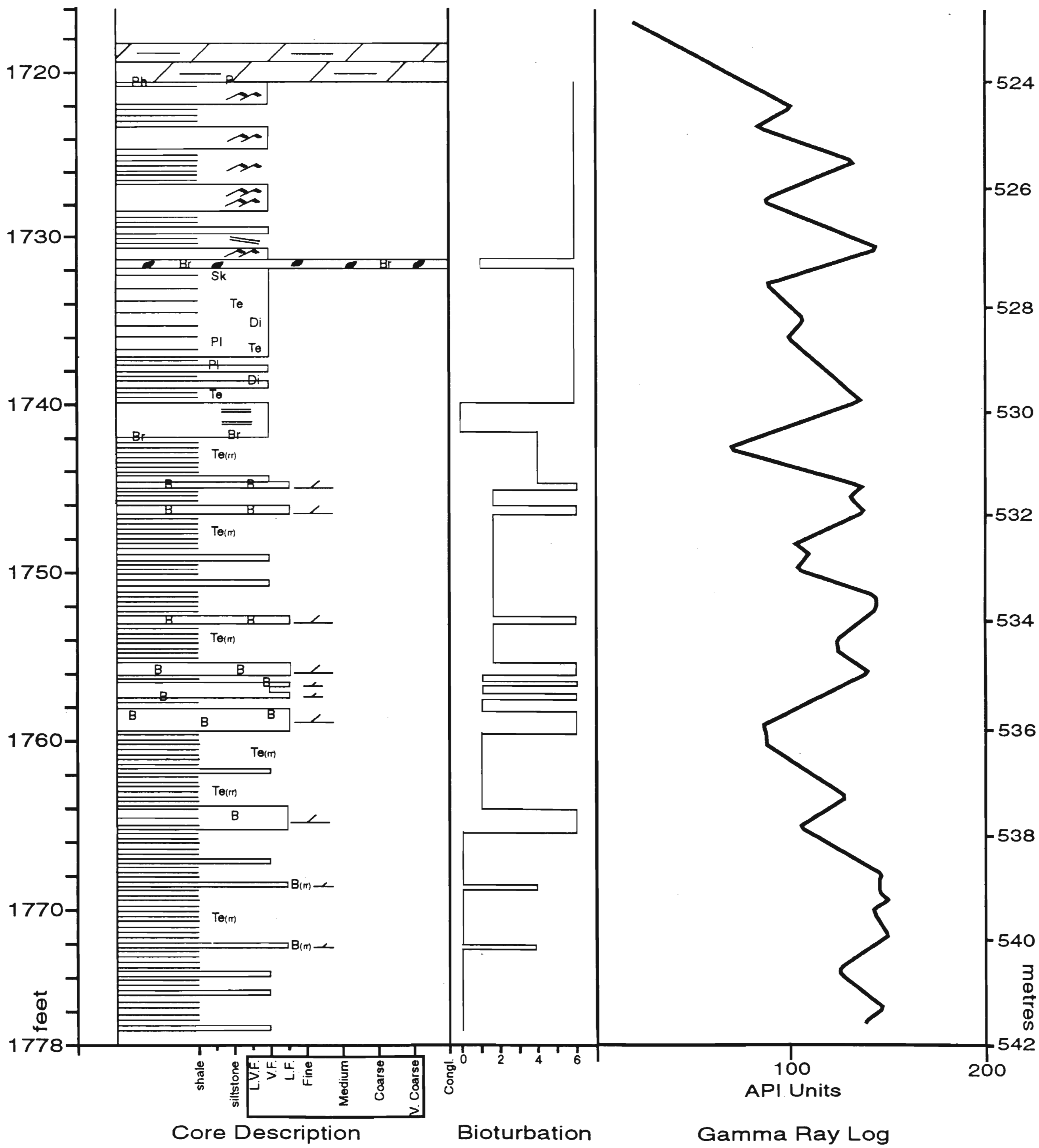


Well Name: Consumers 13112
Block Number: 119-P

Latitude: 42 26' 40.16" N
Longitude: 80 59' 44.98" W

Cored Interval: 1717 - 1777 ft.
523.3 - 541.6 m

K.B. Elev.: 617 ft. 188.1 m
Pet. Res. Core No.: #283

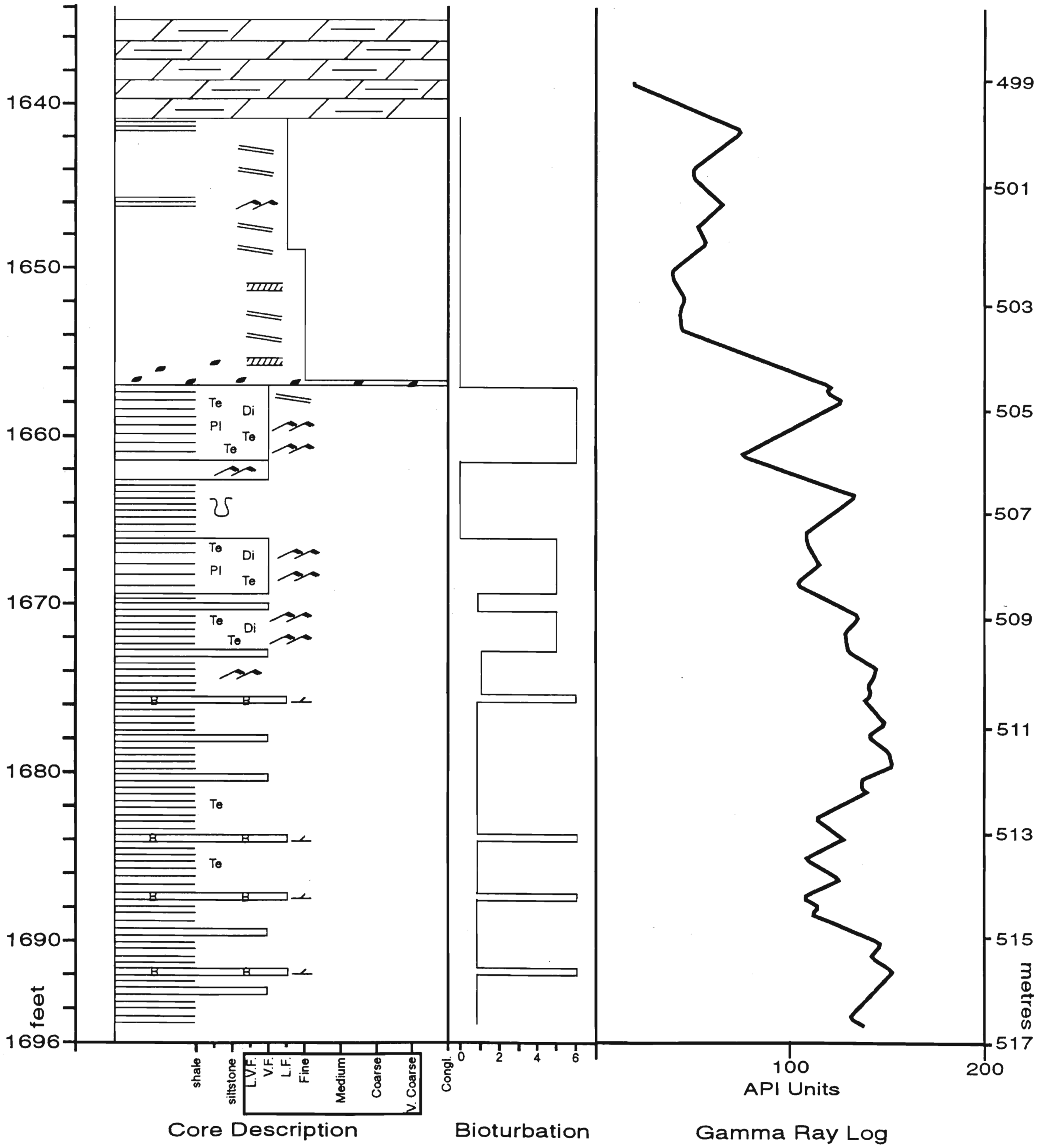


Well Name: Consumers 13013
Block Number: 120-S

Latitude: 42 26' 30.8" N
Longitude: 80 51' 34.5" W

Cored Interval: 1636 - 1695 ft.
498.7 - 516.6 m

K.B. Elev.: 617 ft. 188.1 m
Pet. Res. Core No.: #289

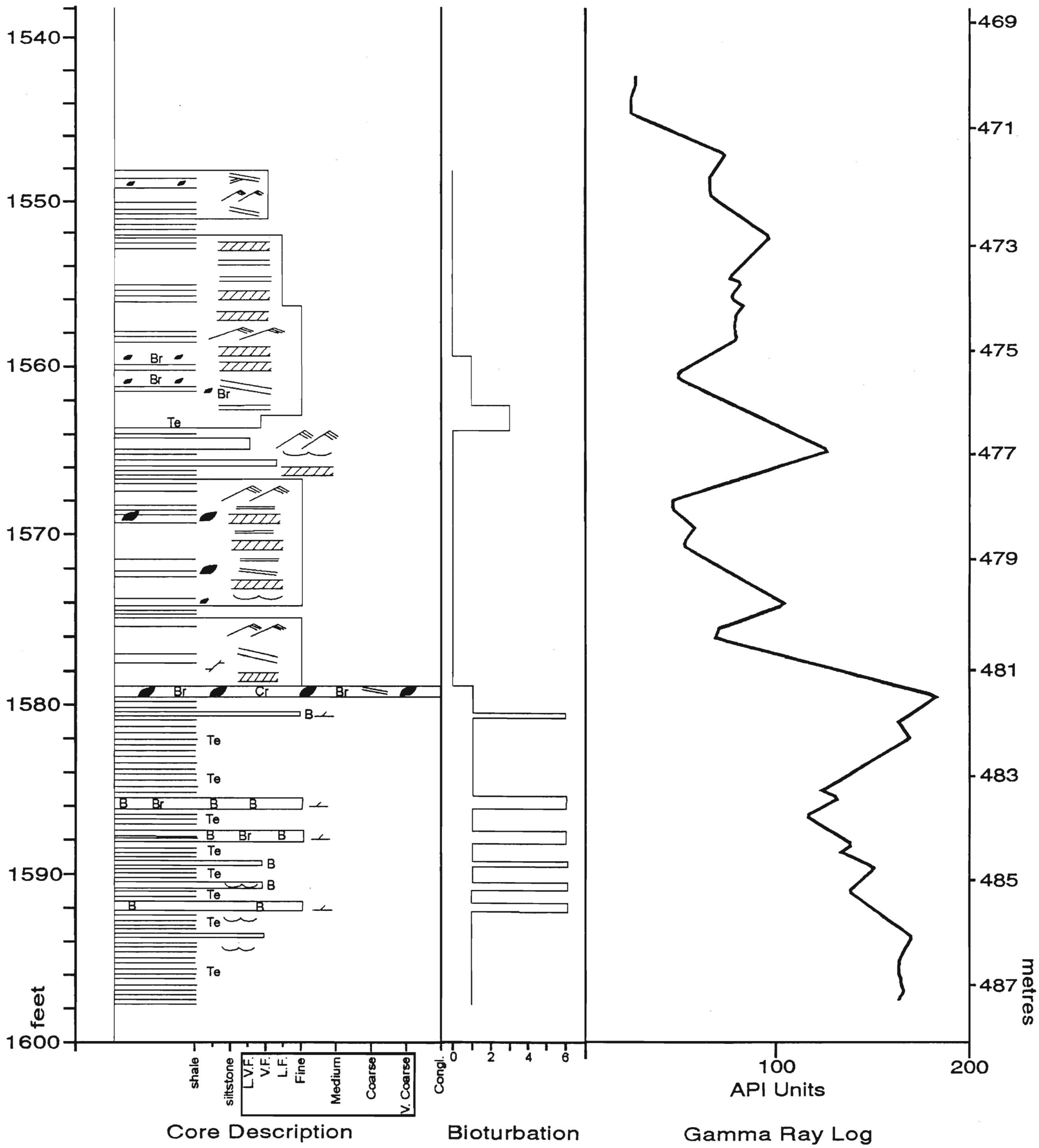


Well Name: Consumers 13224
Block Number: 121-A

Latitude: 42 29' 48.45" N
Longitude: 80 45' 38.40" W

Cored Interval: 1548 - 1598.5 ft.
471.8 - 487.2 m

K.B. Elev.: 620 ft. 189.0 m
Pet. Res. Core No.: #189

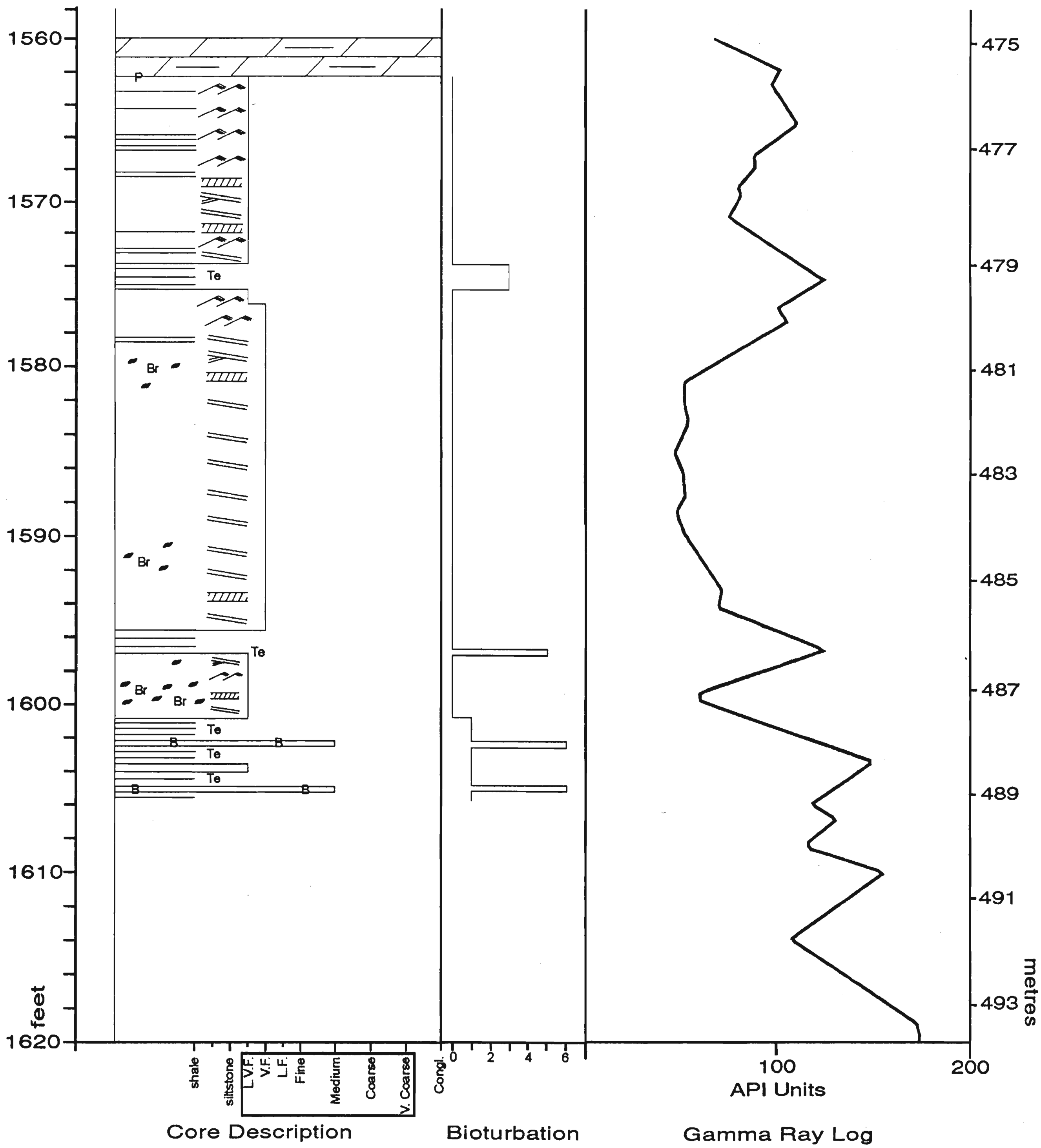


Well Name: Consumers 13229
Block Number: 122-A

Latitude: 42 29' 15.87" N
Longitude: 80 40' 06.16" W

Cored Interval: 1560 - 1605.5 ft.
475.5 - 489.4 m

K.B. Elev.: 619 ft. 188.7 m
Pet. Res. Core No.: #411

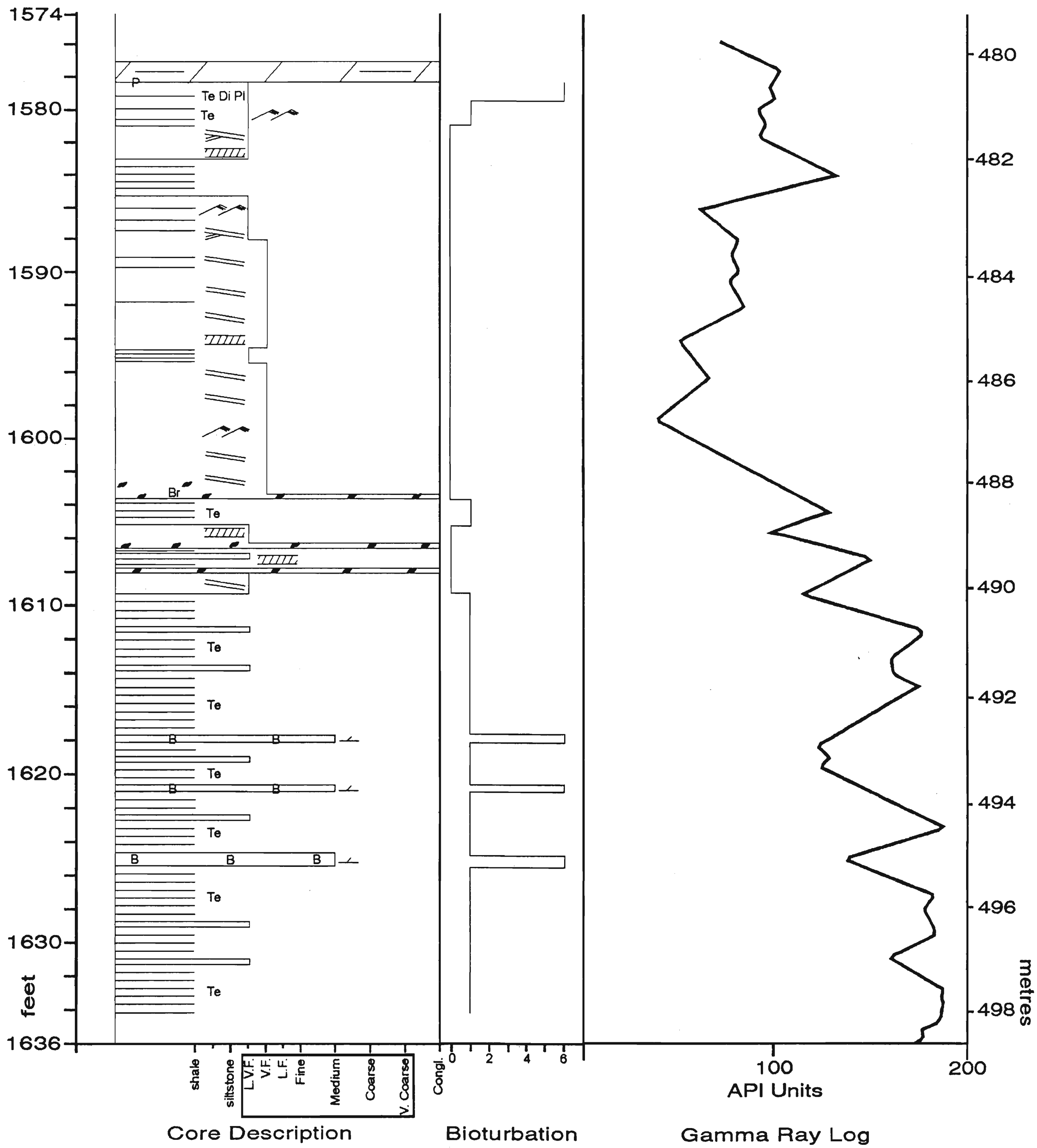


Well Name: Consumers 13198
Block Number: 122-A

Latitude: 42 29' 51.76" N
Longitude: 80 40' 49.03" W

Cored Interval: 1575 - 1634.2 ft.
480.0 - 498.1 m

K.B. Elev.: 619 ft. 188.7 m
Pet. Res. Core No.: #210

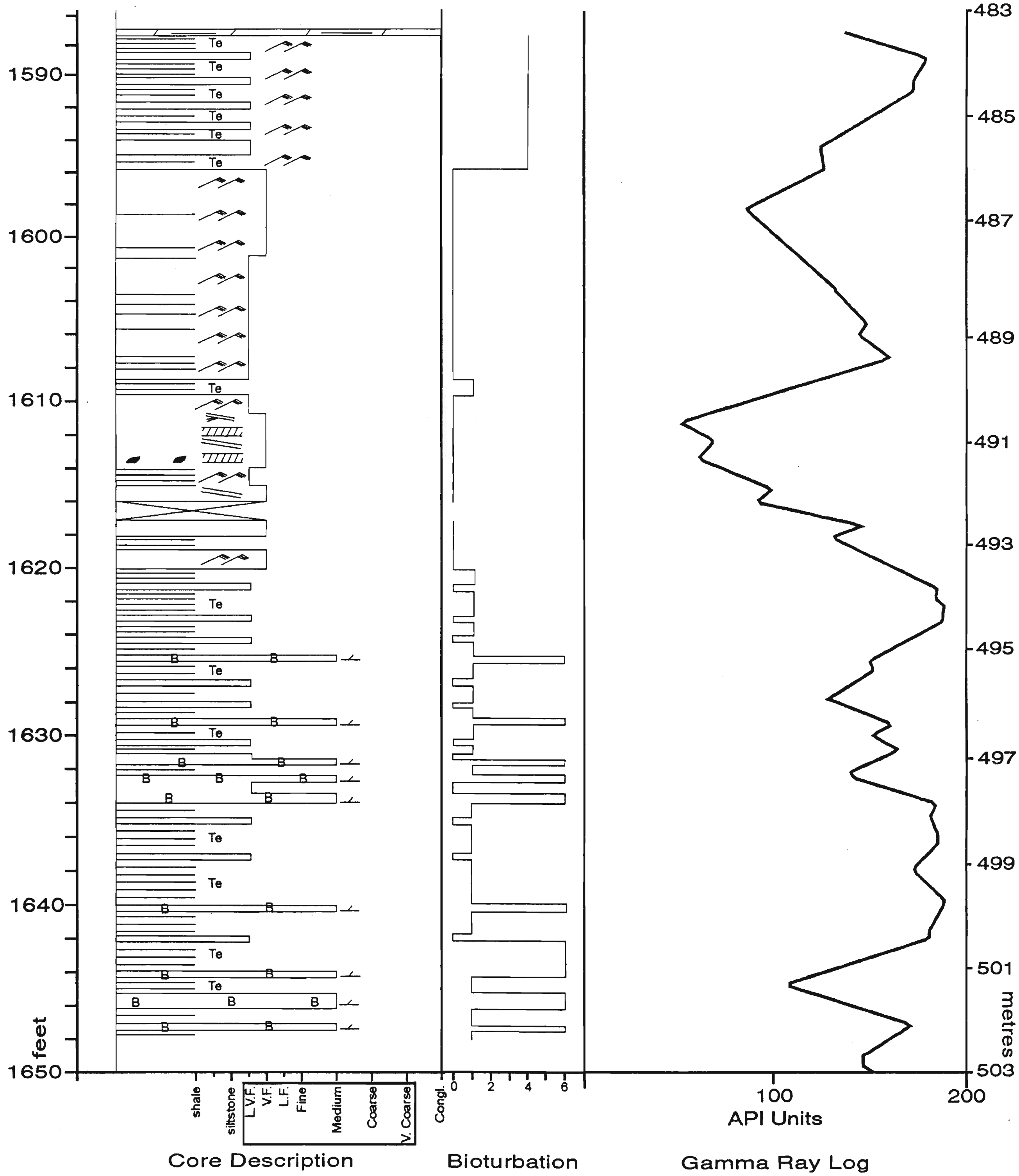


Well Name: Consumers 13151
Block Number: 122-H

Latitude: 42 28' 54.01" N
Longitude: 80 42' 33.25" W

Cored Interval: 1587 - 1647.7 ft.
483.7 - 502.2 m

K.B. Elev.: 619 ft. 188.7 m
Pet. Res. Core No.: #431

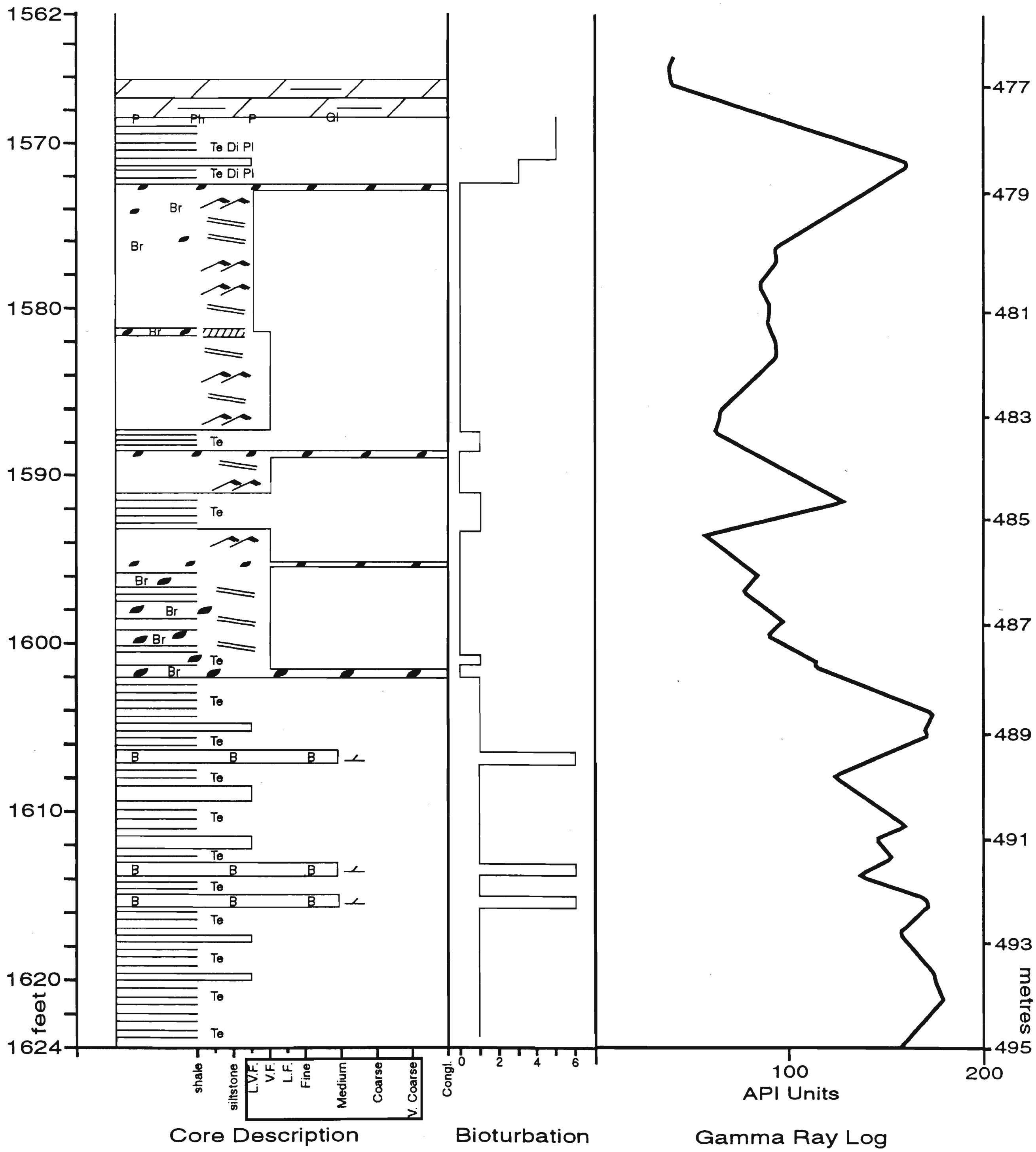


Well Name: Consumers 13152
Block Number: 122-I

Latitude: 42 28' 57.2" N
Longitude: 80 41' 14.9" W

Cored Interval: 1566 - 1623.6 ft.
477.3 - 494.9 m

K.B. Elev.: 619 ft. 188.7 m
Pet. Res. Core No.: #310

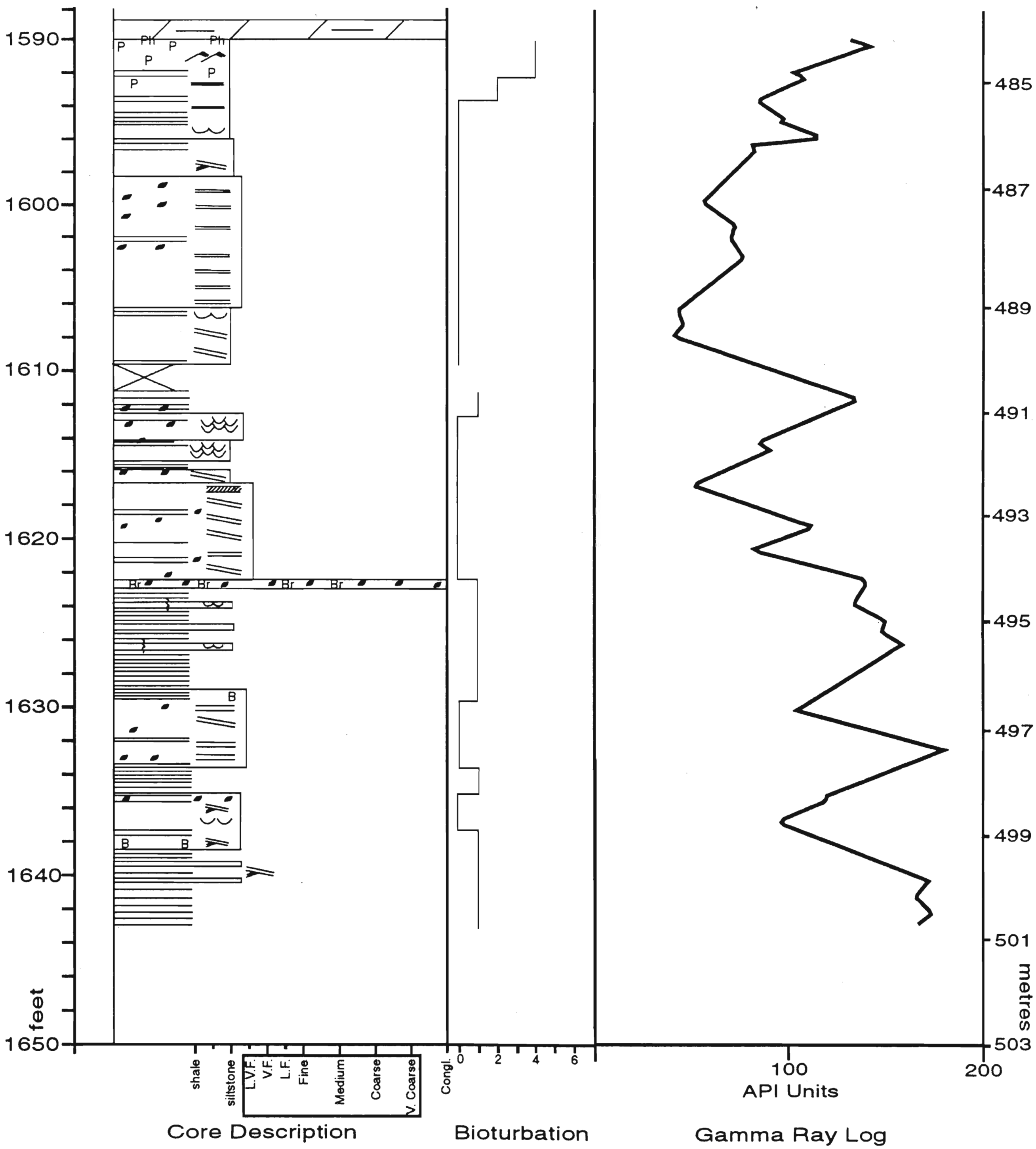


Well Name: Consumers 13153
Block Number: 122-J

Latitude: 42 28' 07.84" N
Longitude: 80 40' 34.19" W

Cored Interval: 1589- 1643 ft.
483.3 - 500.8 m

K.B. Elev.: 618 ft. 188.4 m
Pet. Res. Core No.: #273

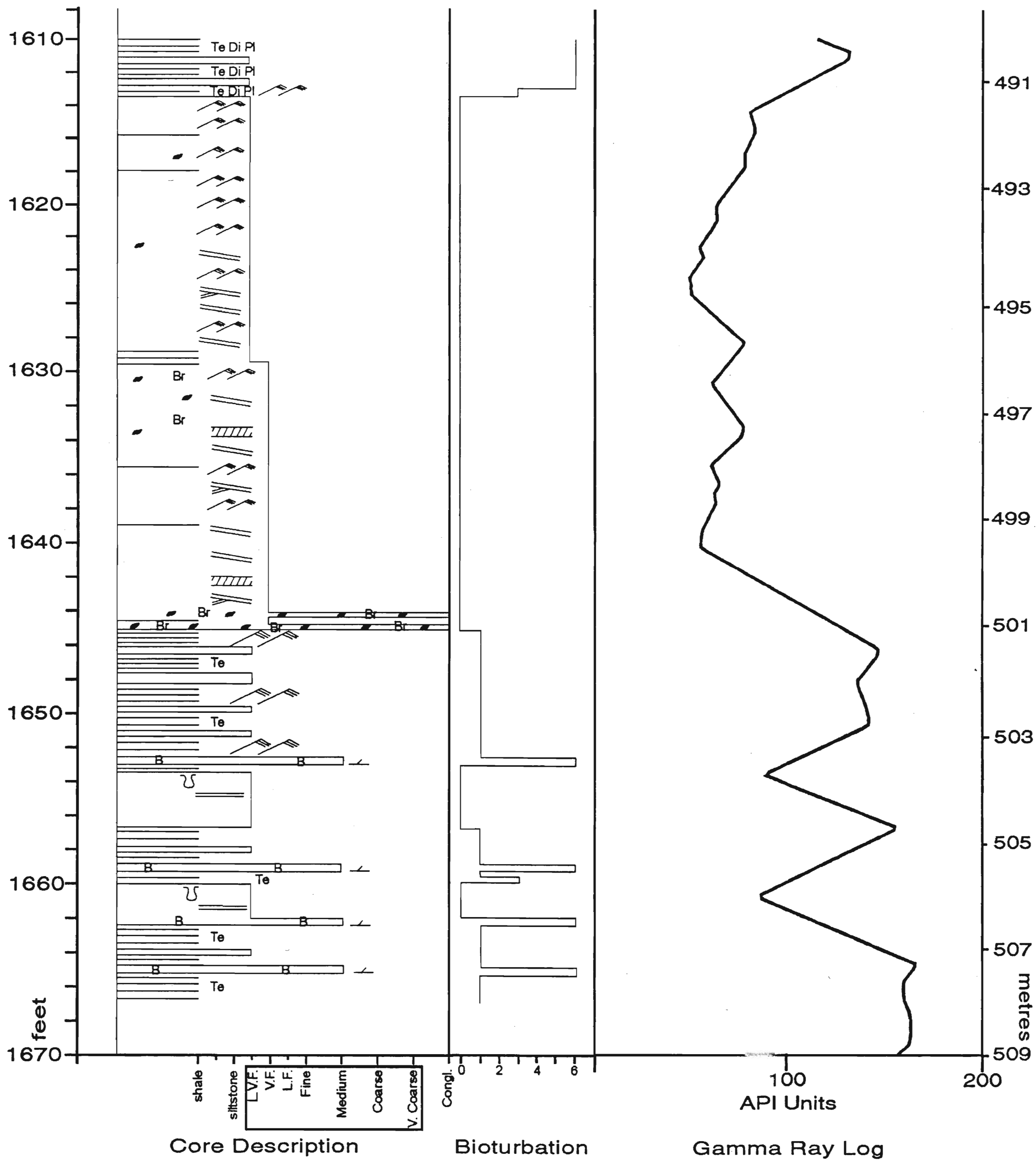


Well Name: Consumers 13214
Block Number: 122-L

Latitude: 42 27' 15.63" N
Longitude: 80 41' 17.23" W

Cored Interval: 1610 - 1666.6 ft.
490.7 - 508.0 m

K.B. Elev.: 617 ft. 188.1 m
Pet. Res. Core No.: #188

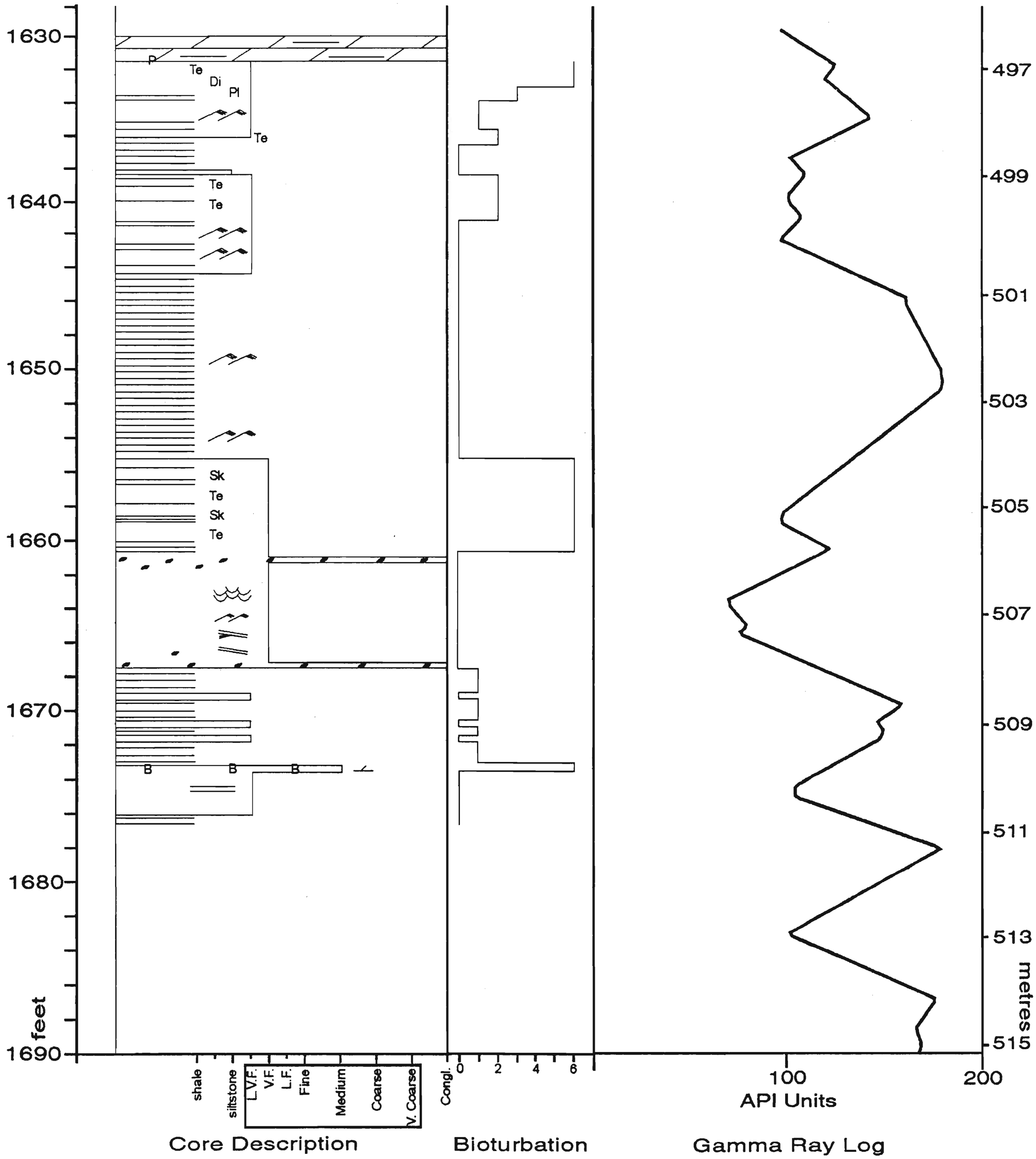


Well Name: Consumers 13228
Block Number: 122-T

Latitude: 42 26' 34.63" N
Longitude: 80 40' 29.07" W

Cored Interval: 1630 - 1676.5 ft.
496.8 - 511.0 m

K.B. Elev.: 619 ft. 188.7 m
Pet. Res. Core No.: #313

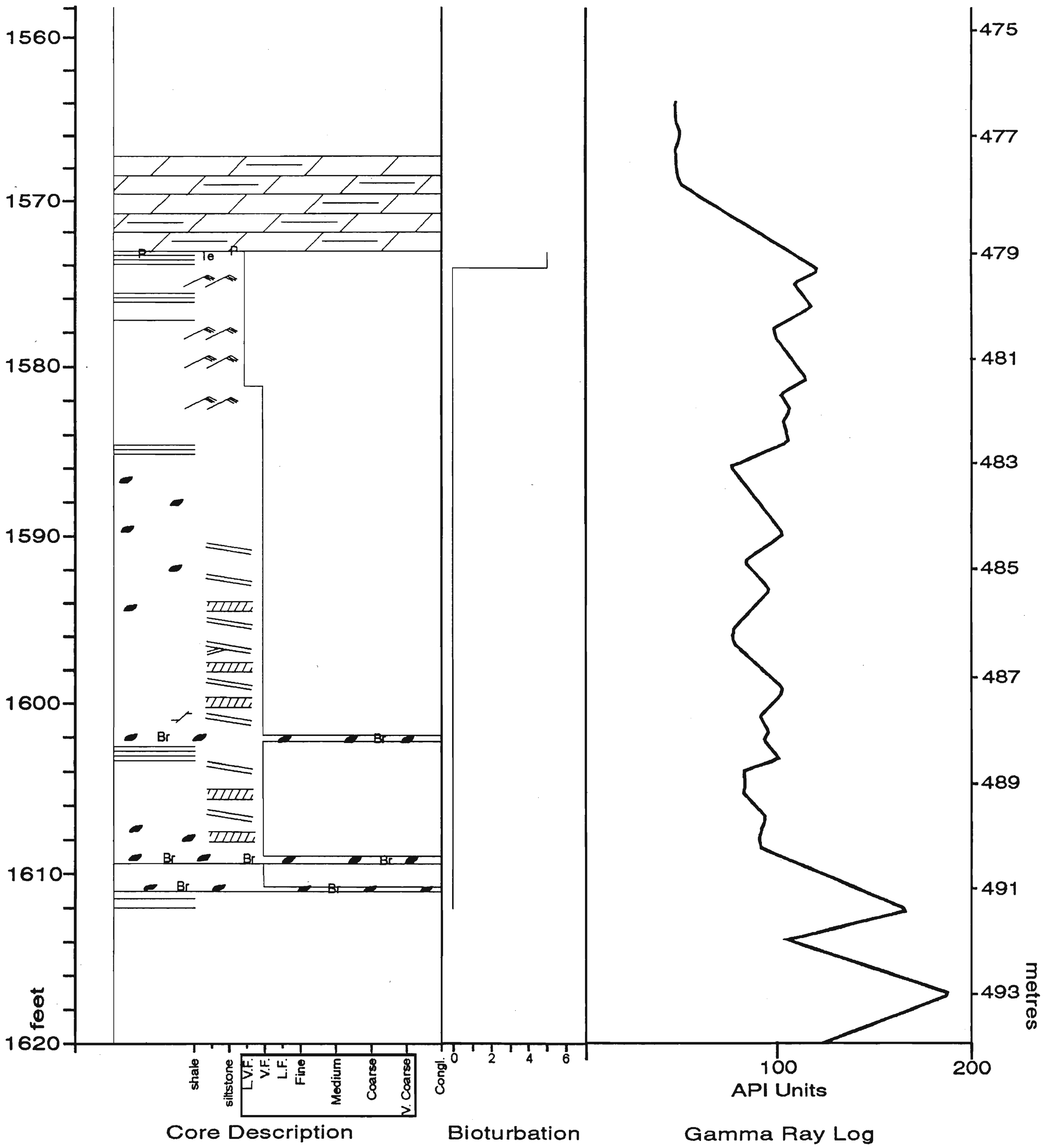


Well Name: Consumers 13237
Block Number: 123-F

Latitude: 42 28' 37.17" N
Longitude: 80 39' 24.85" W

Cored Interval: 1567 - 1612 ft.
477.6 - 491.3 m

K.B. Elev.: 619 ft. 188.7 m
Pet. Res. Core No.: #191

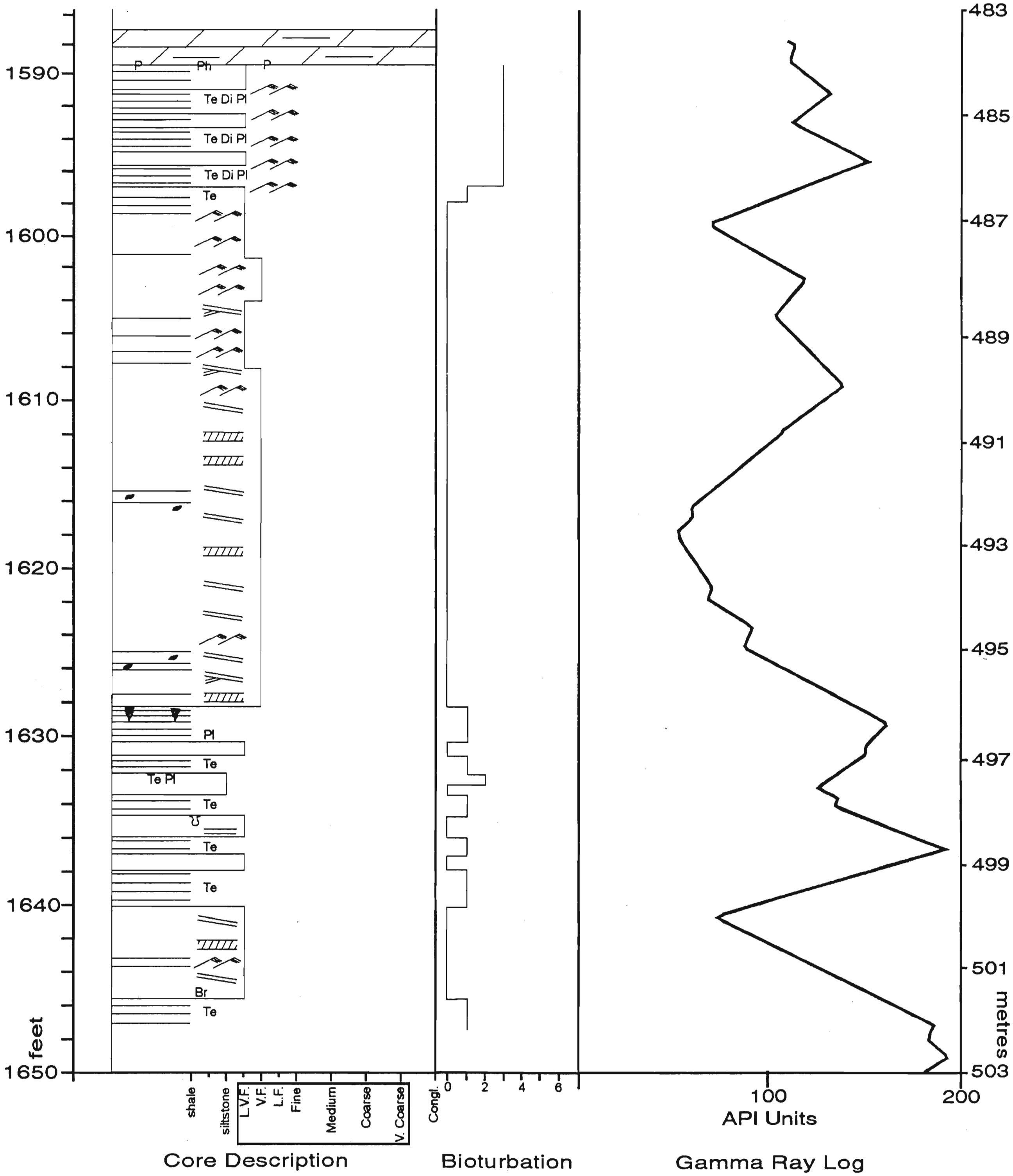


Well Name: Consumers 13147
Block Number: 123-H

Latitude: 42 28' 05.23" N
Longitude: 80 37' 04.43" W

Cored Interval: 1587 - 1647 ft.
483.7 - 502 m

K.B. Elev.: 619 ft. 188.7 m
Pet. Res. Core No.: #264

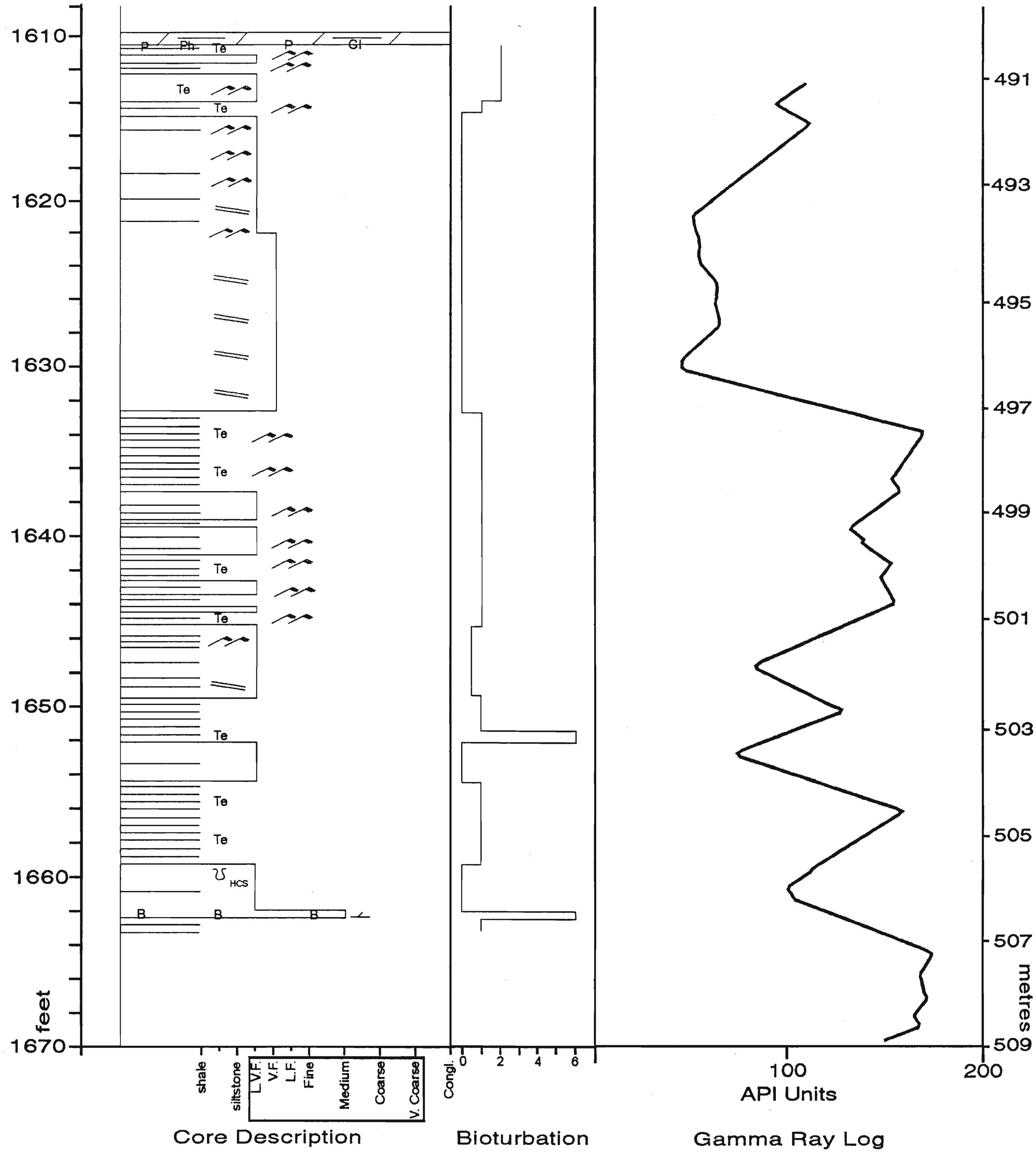


Well Name: Consumers 13221
Block Number: 123-0

Latitude: 42 27' 19.37" N
Longitude: 80 39' 53.90" W

Cored Interval: 1610 - 1663.3 ft.
490.7 - 507.0 m

K.B. Elev.: 619 ft. 188.7 m
Pet. Res. Core No.: #350

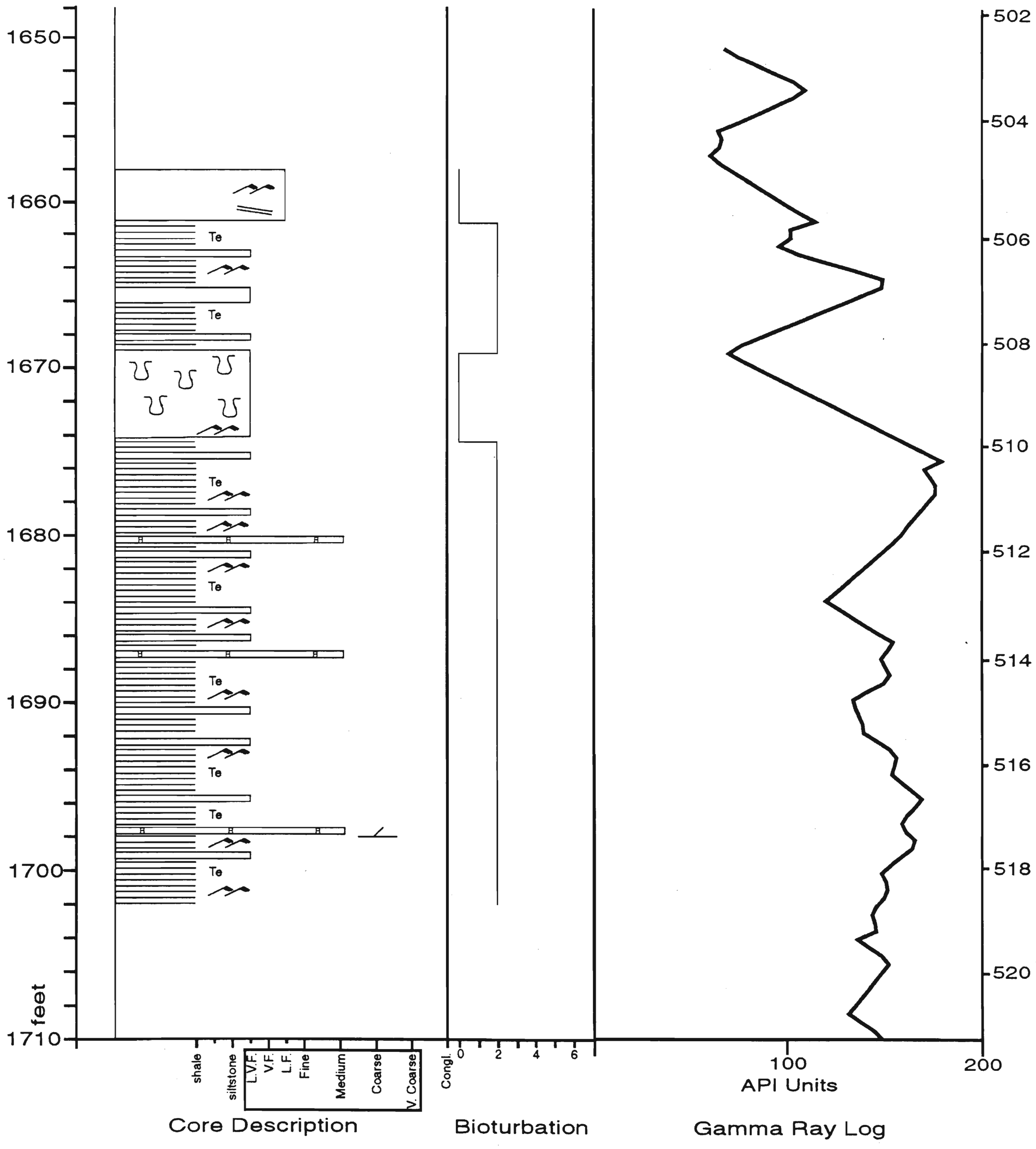


Well Name: Consumers 13044
Block Number: 123-Q

Latitude: 42 26' 14" N
Longitude: 80 38' 00" W

Cored Interval: 1658 - 1718 ft. (1702-1718' lost)
505.4 - 523.6 m

K.B. Elev.: 600 ft. 182.9 m
Pet. Res. Core No.: #809

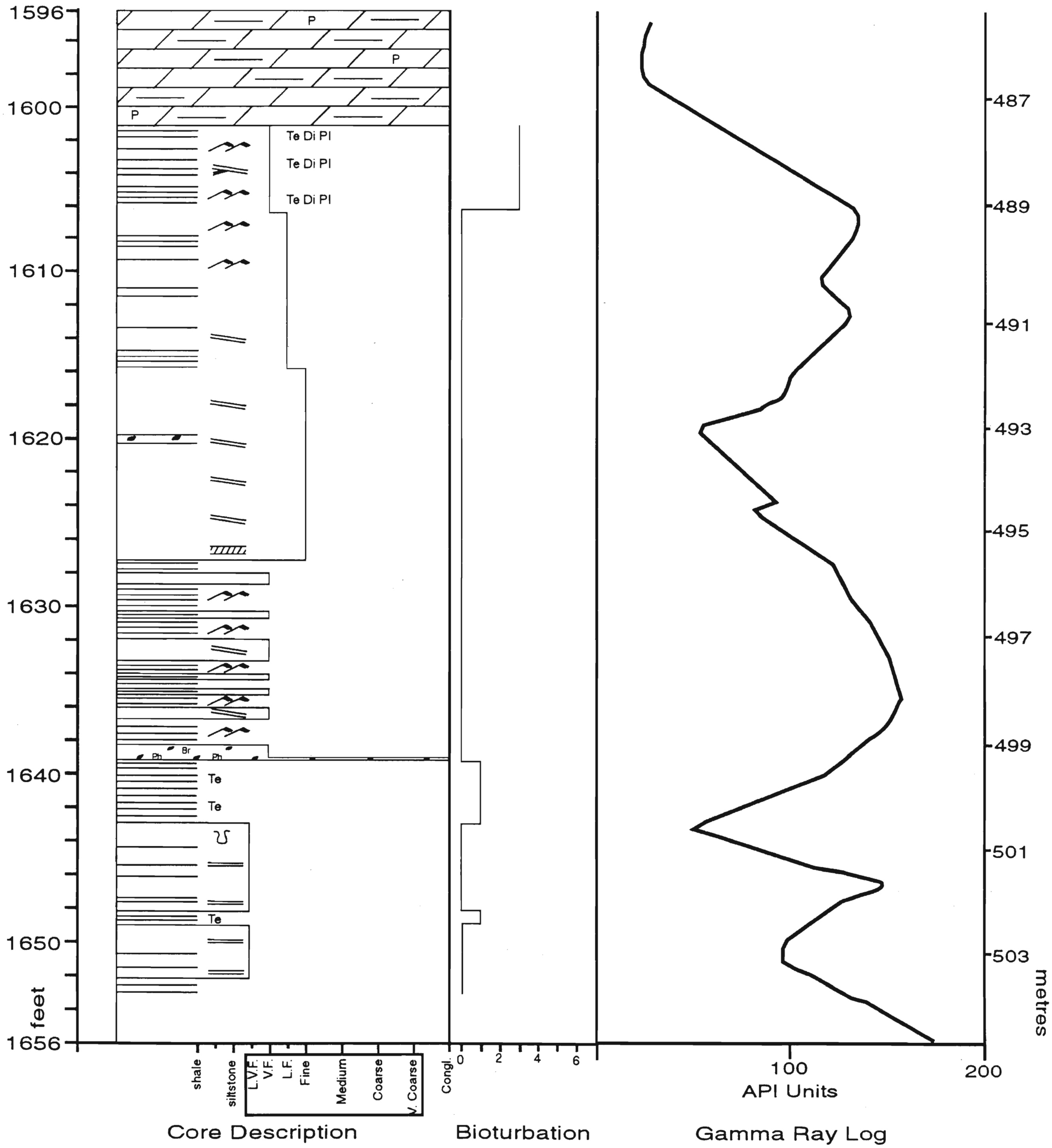


Well Name: Consumers 13089
Block Number: 123-T

Latitude: 42 26' 31" N
Longitude: 80 35' 25" W

Cored Interval: 1596 - 1656 ft. (1653-56' lost)
486.5 - 504.7 m

K.B. Elev.: 615 ft. 187.5 m
Pet. Res. Core No.: #306

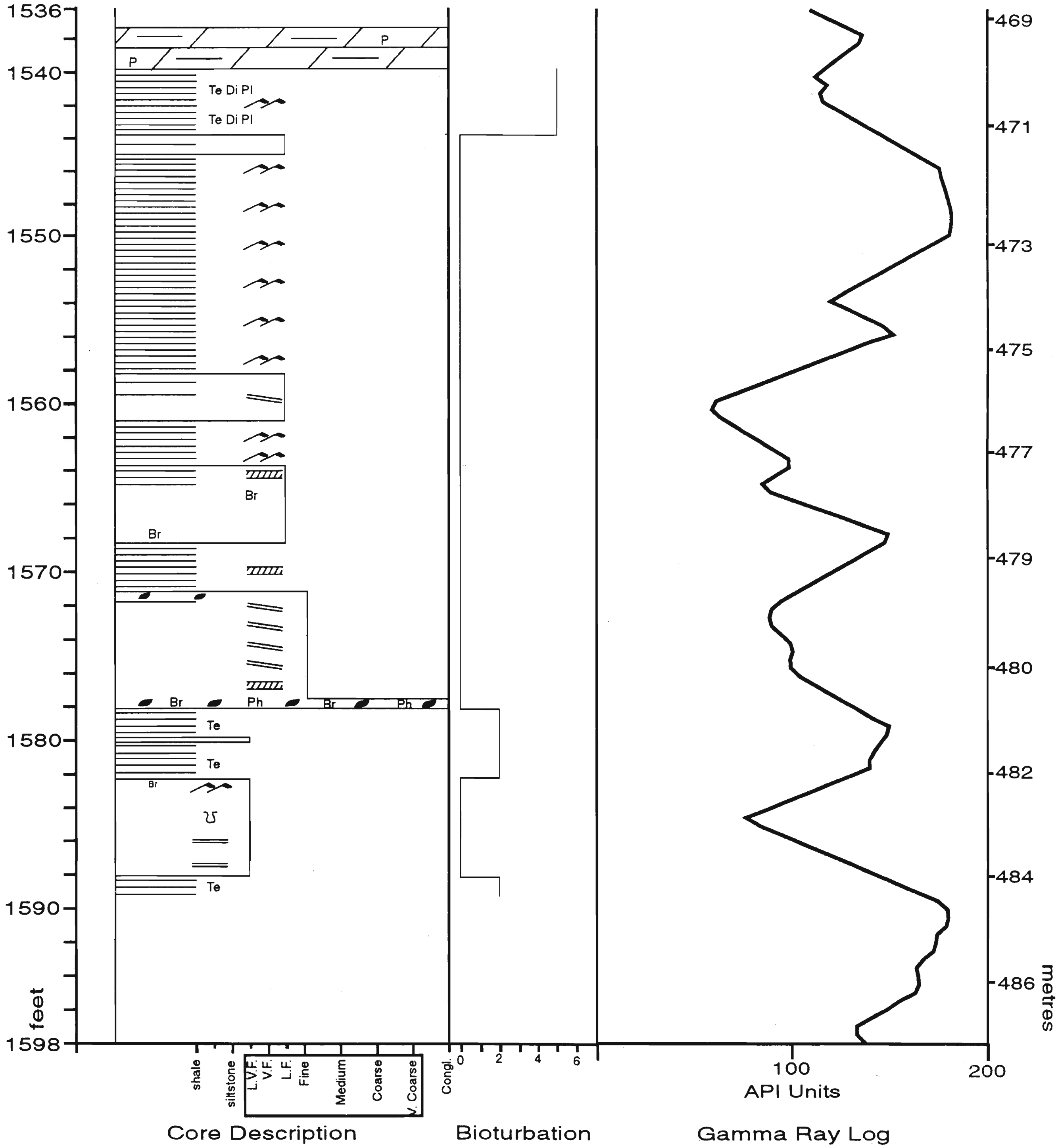


Well Name: Consumers 13094
Block Number: 124-C

Latitude: 42 29' 04.61" N
Longitude: 80 32' 57.50" W

Cored Interval: 1537 - 1597 ft. (1589-97 lost)
468.5 - 486.8 m

K.B. Elev.: 602 ft. 183.5 m
Pet. Res. Core No.: #168

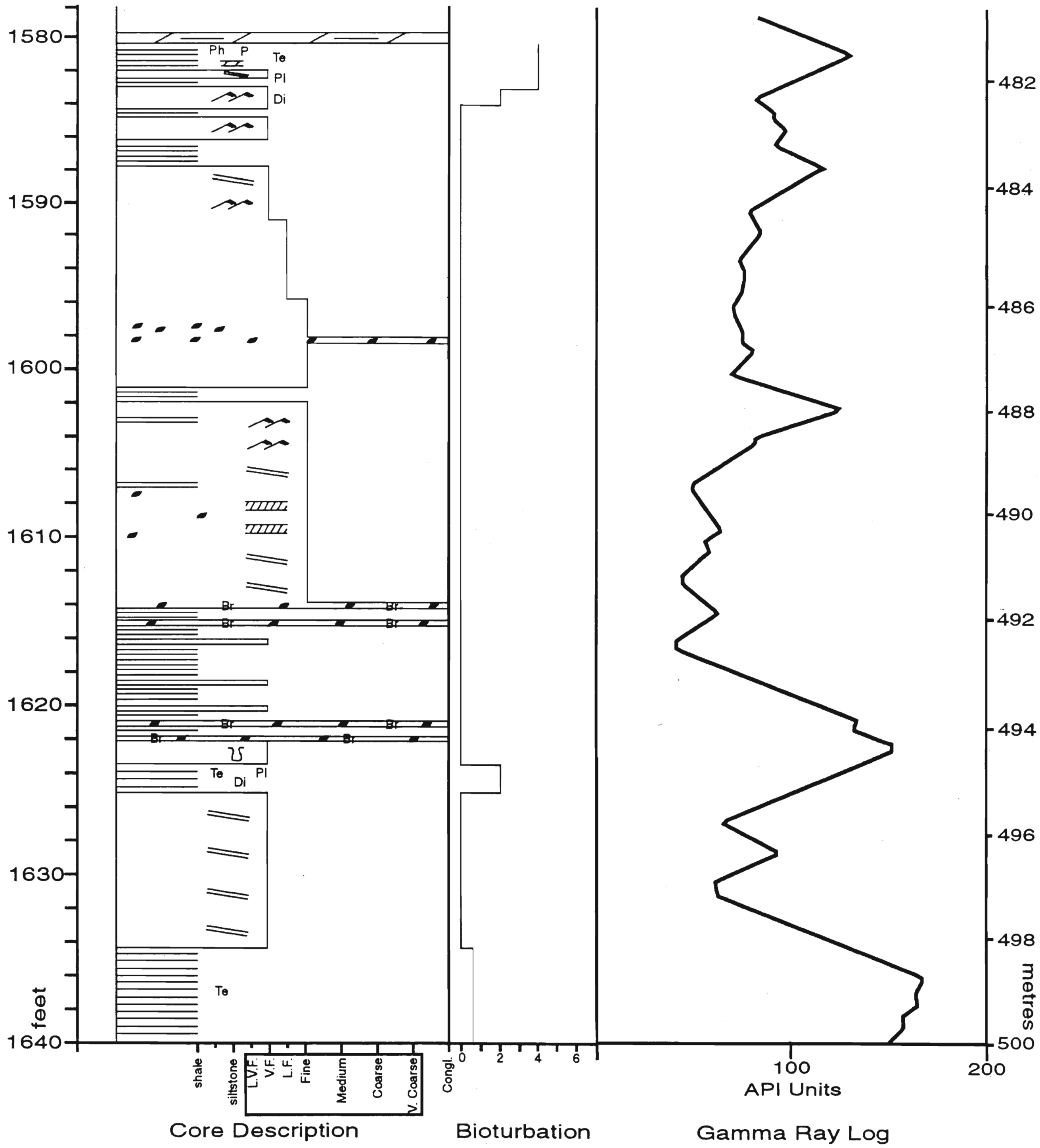


Well Name: Consumers 13117
Block Number: 124-G

Latitude: 42 28' 13.4" N
Longitude: 80 33' 06.6" W

Cored Interval: 1580 - 1640 ft.
481.6 - 499.9 m

K.B. Elev.: 616 ft. 187.8 m
Pet. Res. Core No.: #272

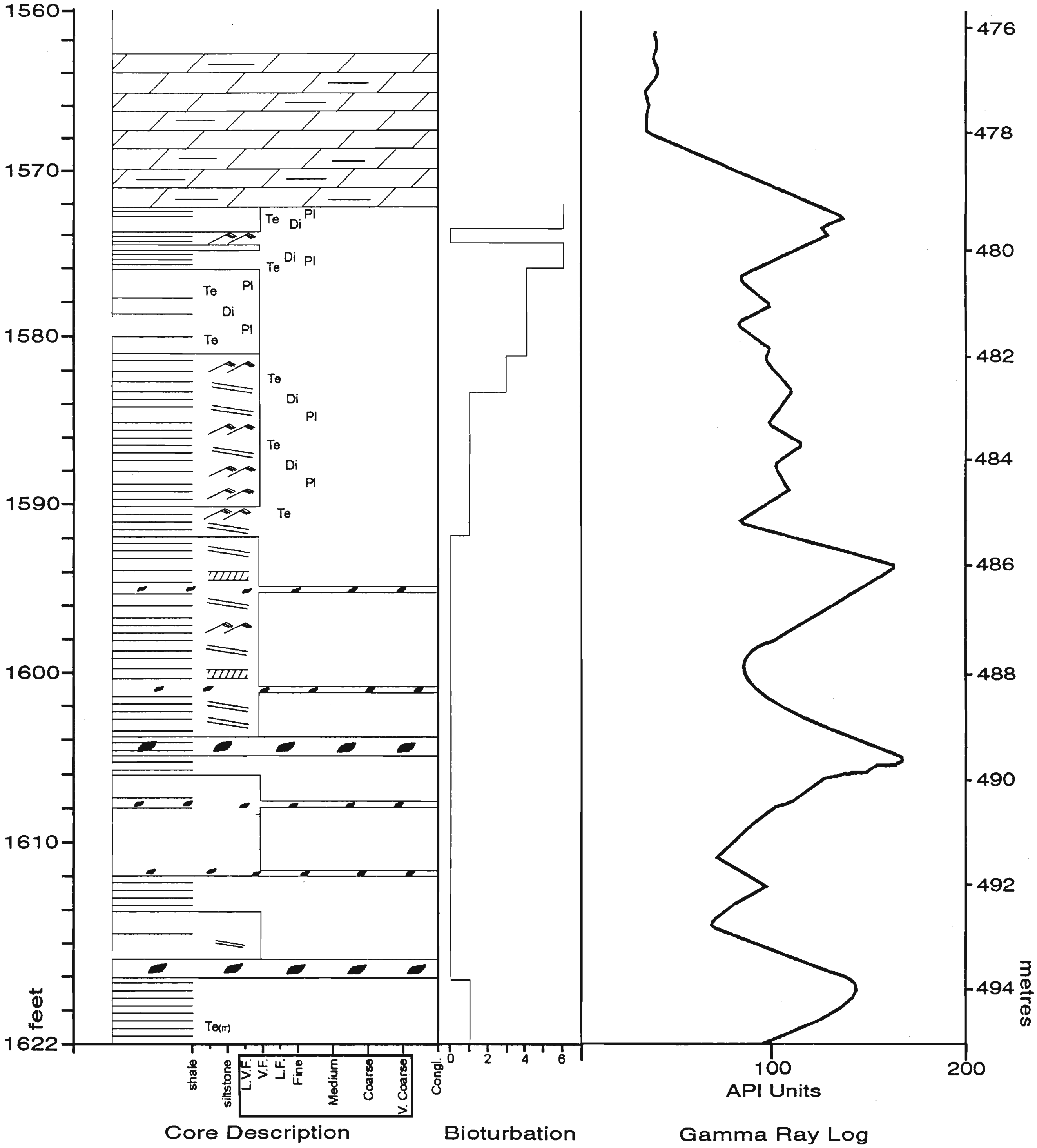


Well Name: Consumers 13132
Block Number: 124-G

Latitude: 42 28' 22.15" N
Longitude: 80 33' 29.45" W

Cored Interval: 1562 - 1622 ft.
476.1 - 494.4 m

K.B. Elev.: 614 ft. 187.5 m
Pet. Res. Core No.: #441

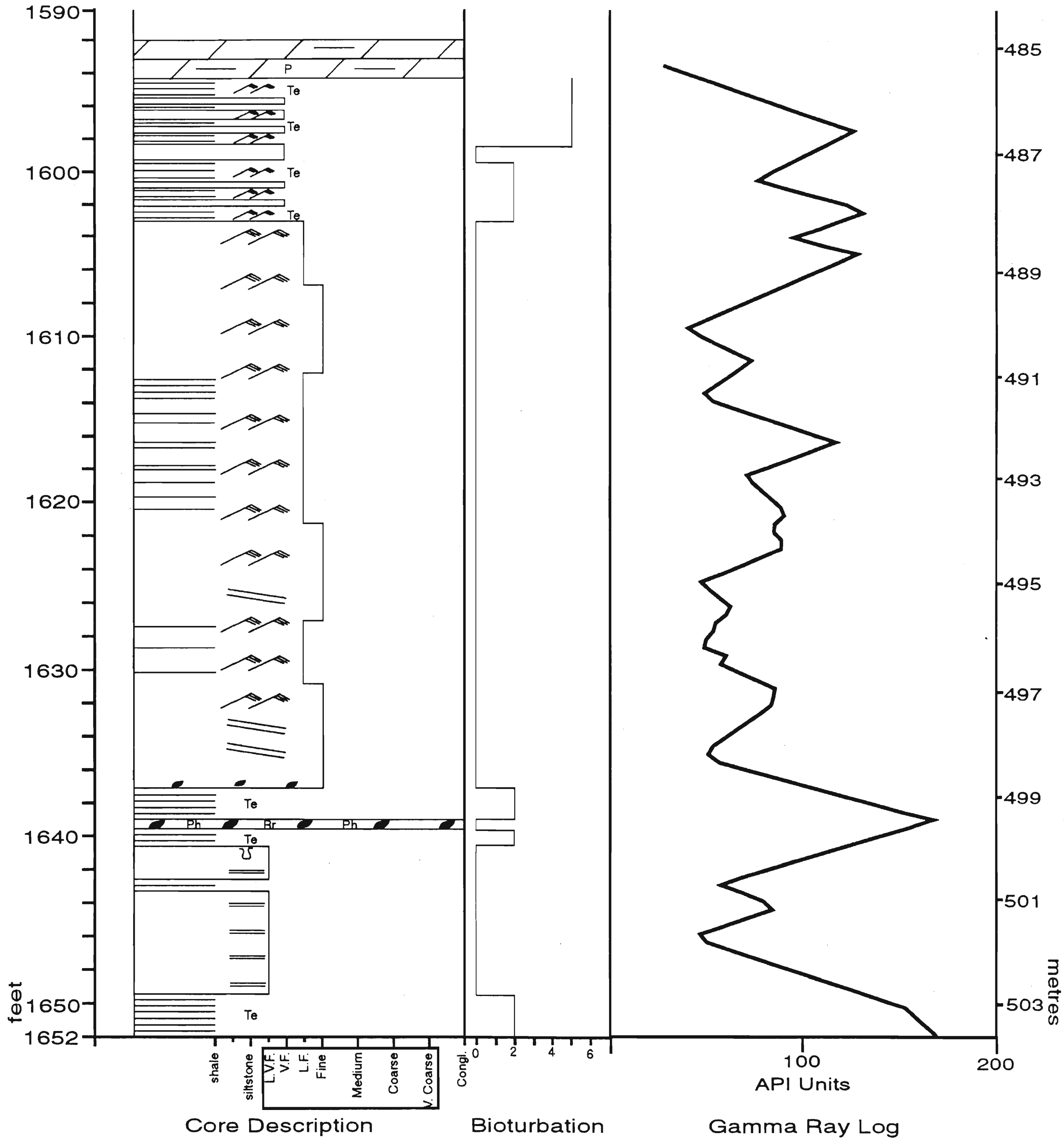


Well Name: Consumers 13154
Block Number: 124-N

Latitude: 42 27' 24.09" N
Longitude: 80 33' 12.70" W

Cored Interval: 1592 - 1652 ft.
485.2 - 503.5 m

K.B. Elev.: 618 ft. 188.4 m
Pet. Res. Core No.: #449

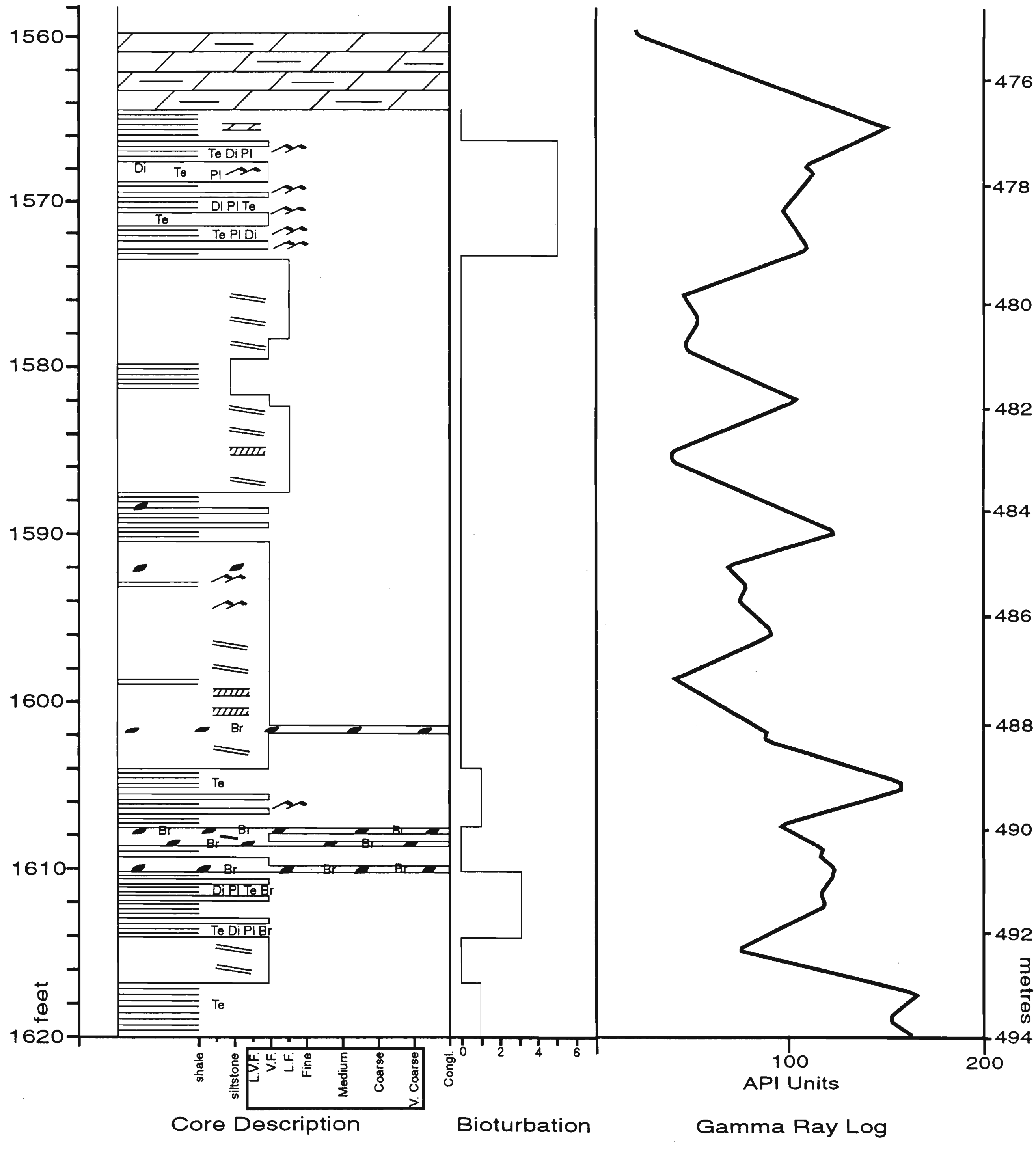


Well Name: Consumers 13329
Block Number: 125-F

Latitude: 42 28' 33.47" N
Longitude: 80 29' 55.01" W

Cored Interval: 1560 - 1620 ft.
475.5 - 493.8 m

K.B. Elev.: 597 ft. 182.0 m
Pet. Res. Core No.: #663

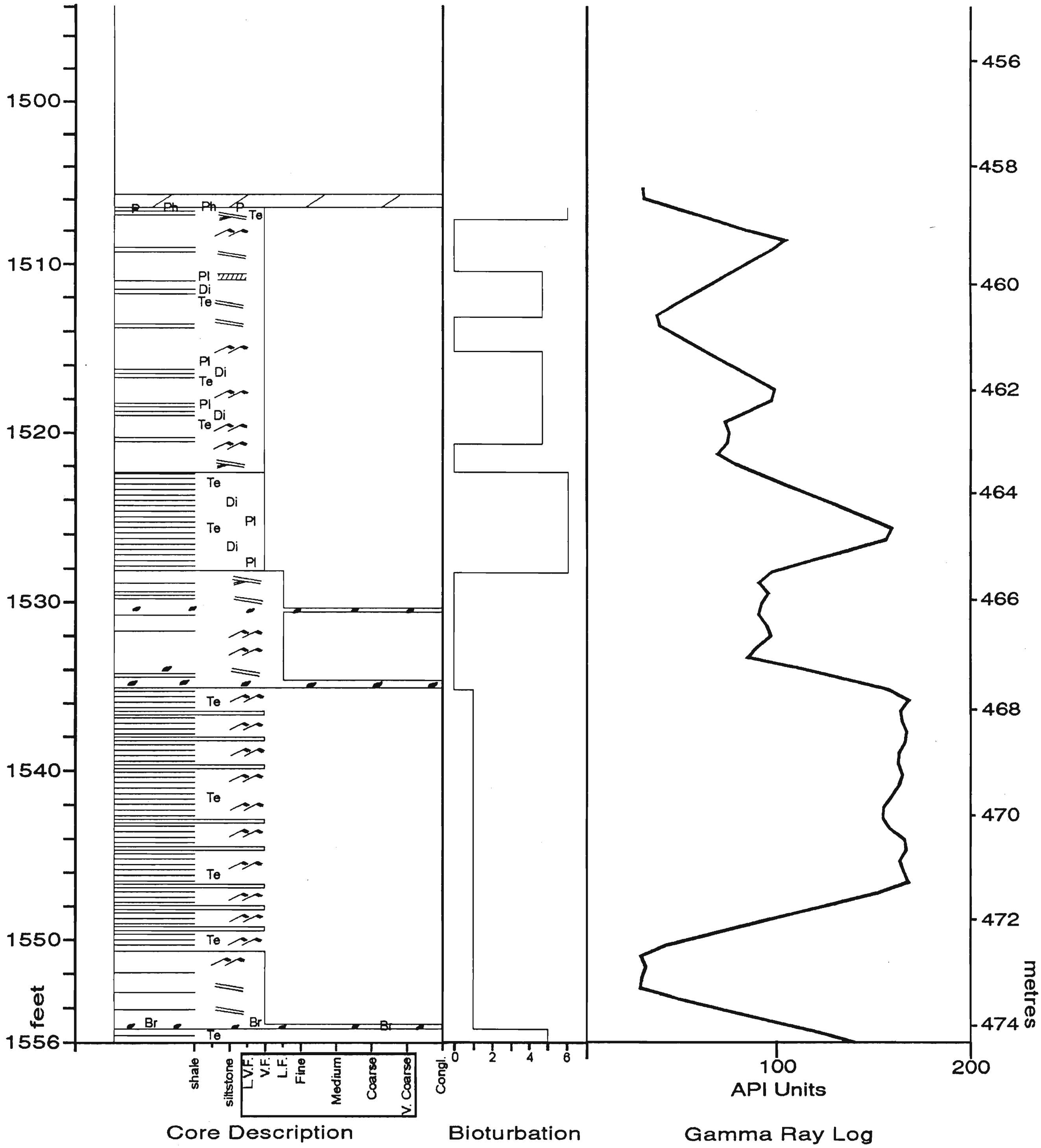


Well Name: Telesis 13926
Block Number: 126-A-4

Latitude: 42 29' 19.78" N
Longitude: 80 20' 12.68" W

Cored Interval: 1506 - 1556 ft.
459.0 - 474.16 m

K.B. Elev.: 595 ft. 181.2 m
Pet. Res. Core No.: #1022

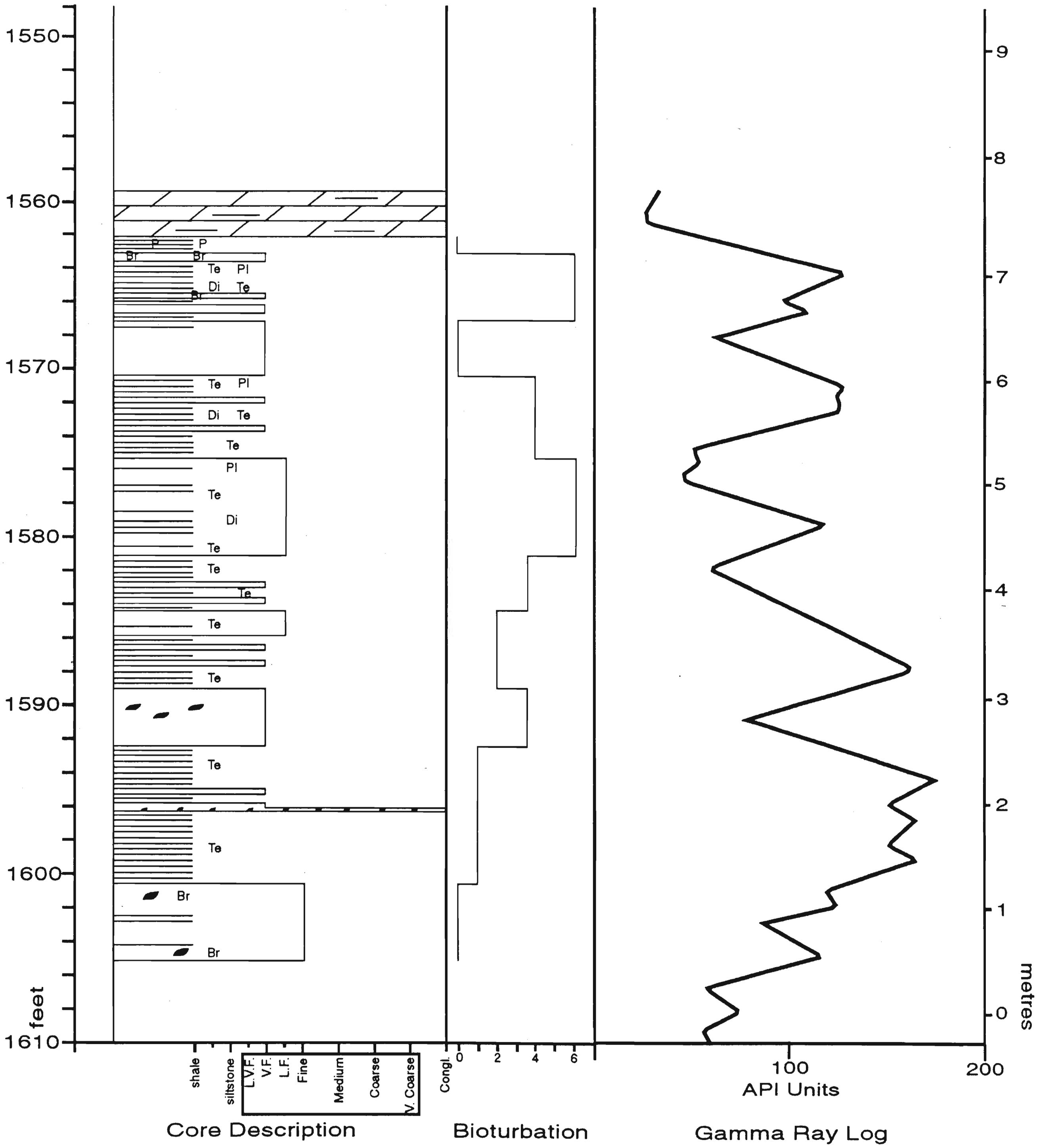


Well Name: CPOG Haldimand #1
Block Number: 131-G

Latitude: 42 28' 18.86" N
Longitude: 79 58' 10.92" W

Cored Interval: 1559 - 1608 ft. (1605-08 lost)
475.2 - 490.1 m

K.B. Elev.: 599 ft. 182.6 m
Pet. Res. Core No.: #146

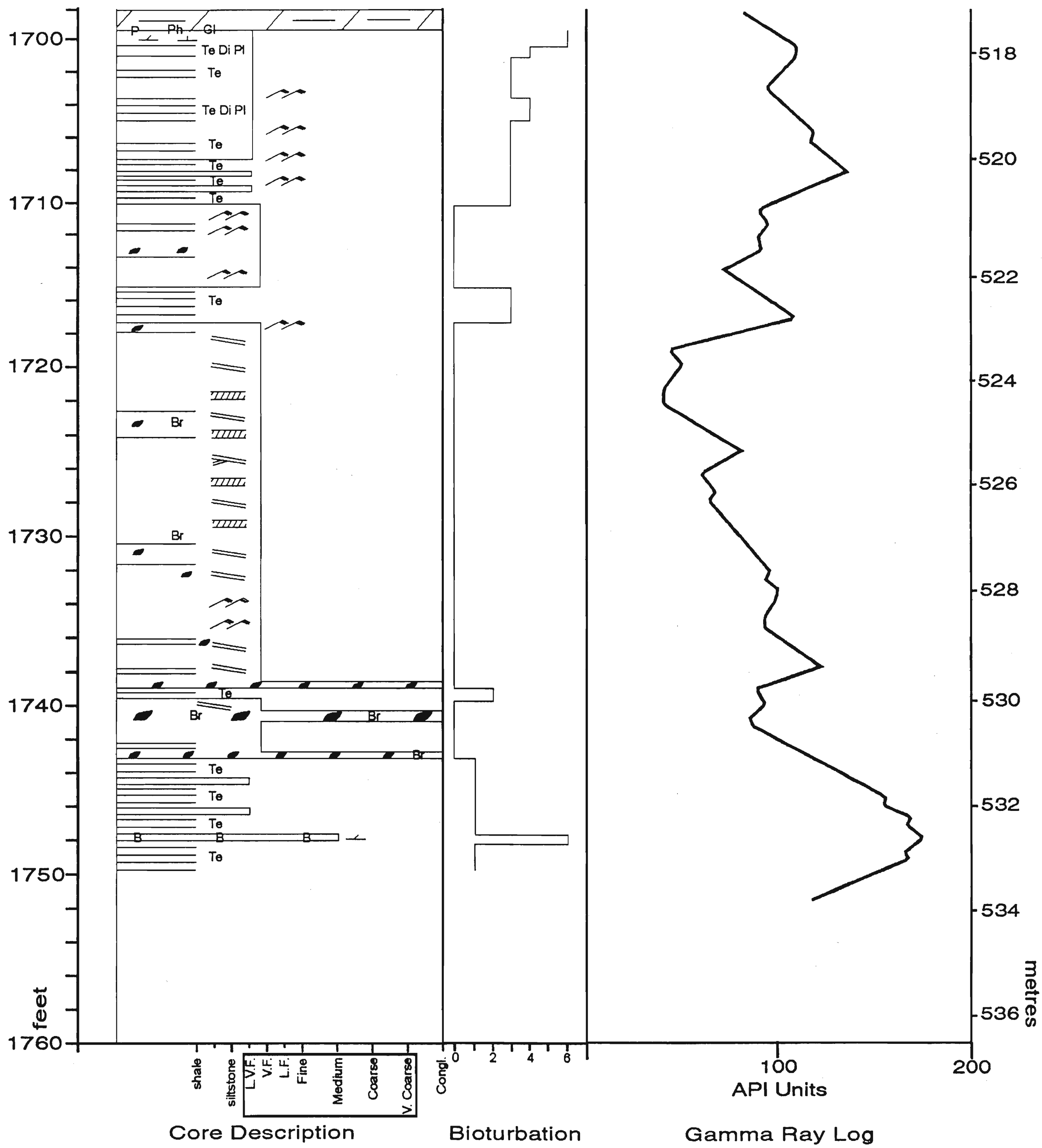


Well Name: Consumers 13185
Block Number: 152-B

Latitude: 42 24' 39.63" N
Longitude: 80 26' 47.39" W

Cored Interval: 1698 - 1749.7 ft.
517.6 - 533.3 m

K.B. Elev.: 619 ft. 188.7 m
Pet. Res. Core No.: #295

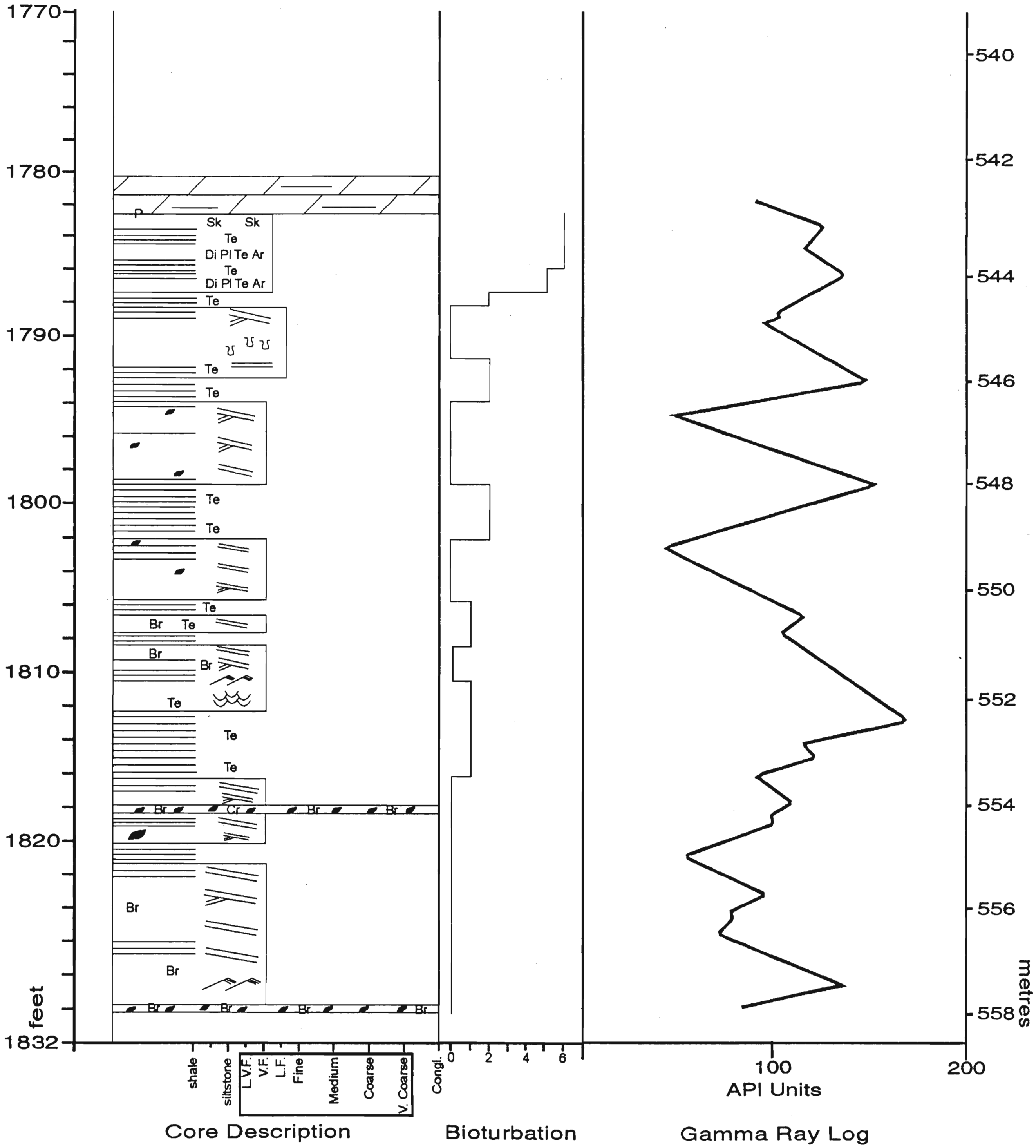


Well Name: Consumers 13167
Block Number: 152-N

Latitude: 42 22' 10.81" N
Longitude: 80 28' 36.21" W

Cored Interval: 1780 - 1830 ft.
542.5 - 557.8 m

K.B. Elev.: 616 ft. 187.8 m
Pet. Res. Core No.: #336

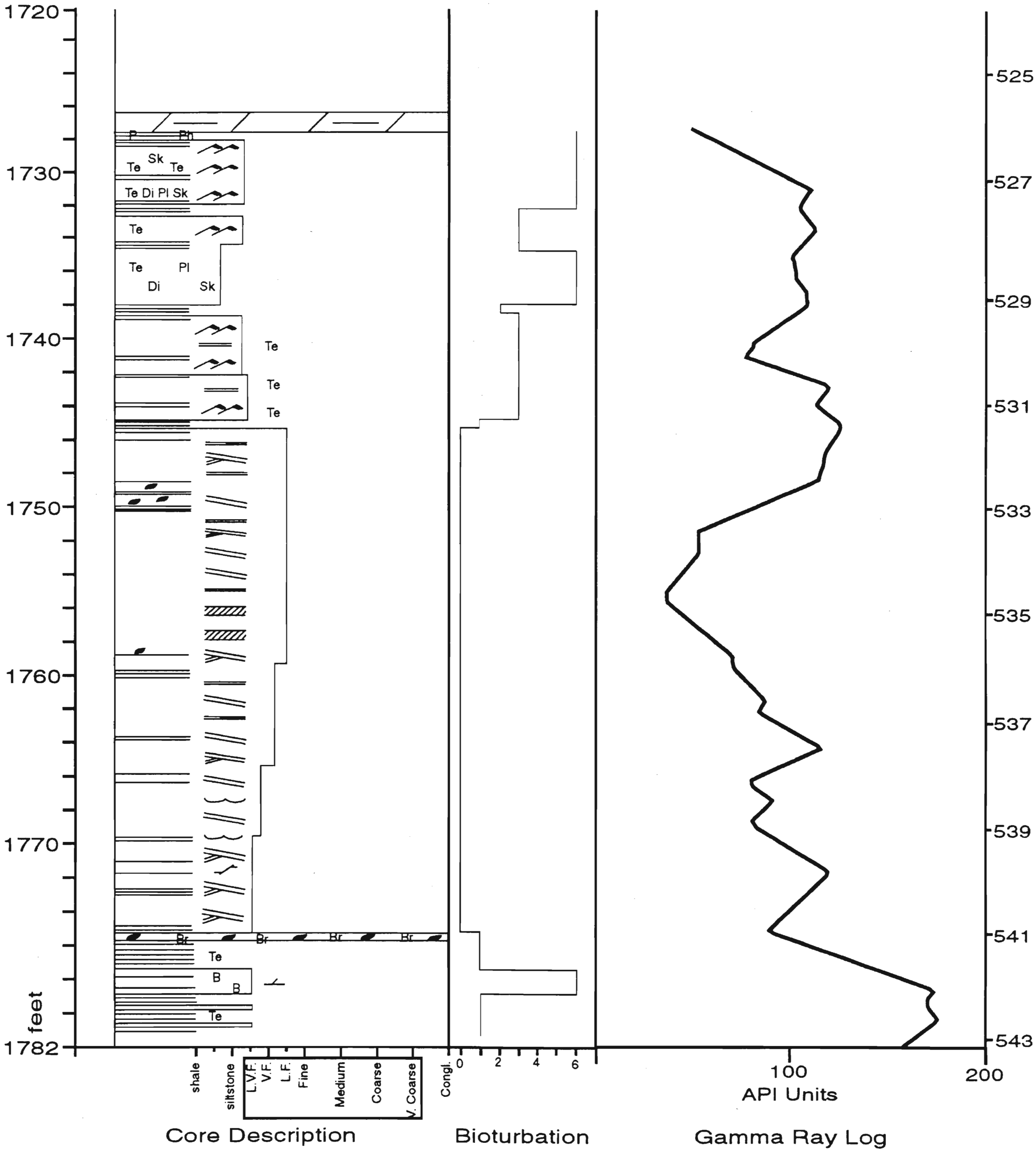


Well Name: Consumers 13197
Block Number: 153-H

Latitude: 42 23' 07.90" N
Longitude: 80 32' 29.85" W

Cored Interval: 1726 - 1782 ft.
526.1 - 543.2 m

K.B. Elev.: 615 ft. 187.5 m
Pet. Res. Core No.: #274

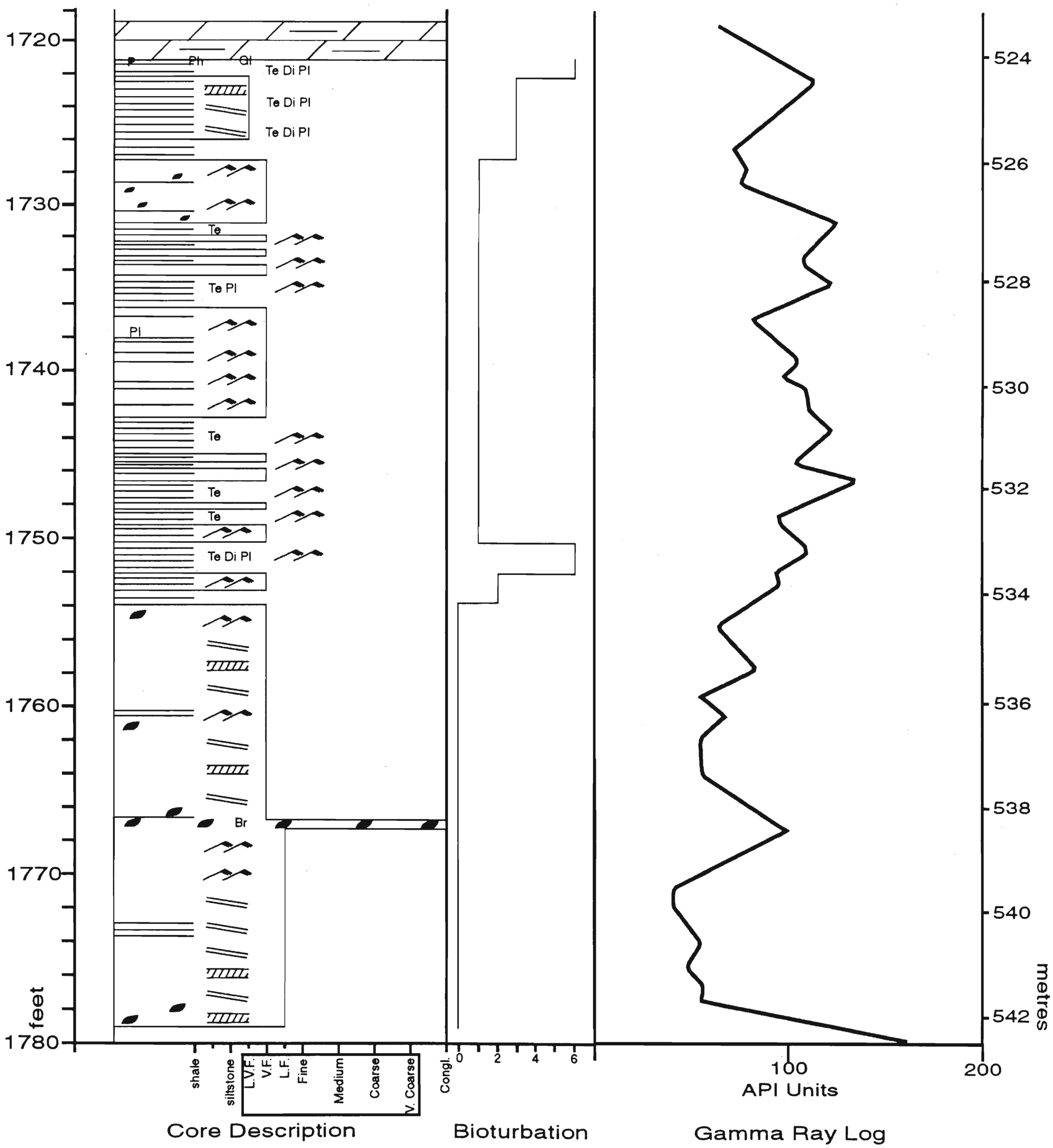


Well Name: Consumers 13223
Block Number: 154-G

Latitude: 42 23' 50.05" N
Longitude: 80 38' 55.11" W

Cored Interval: 1719 - 1779 ft.
524.0 - 542.2 m

K.B. Elev.: 619 ft. 188.7 m
Pet. Res. Core No.: #414

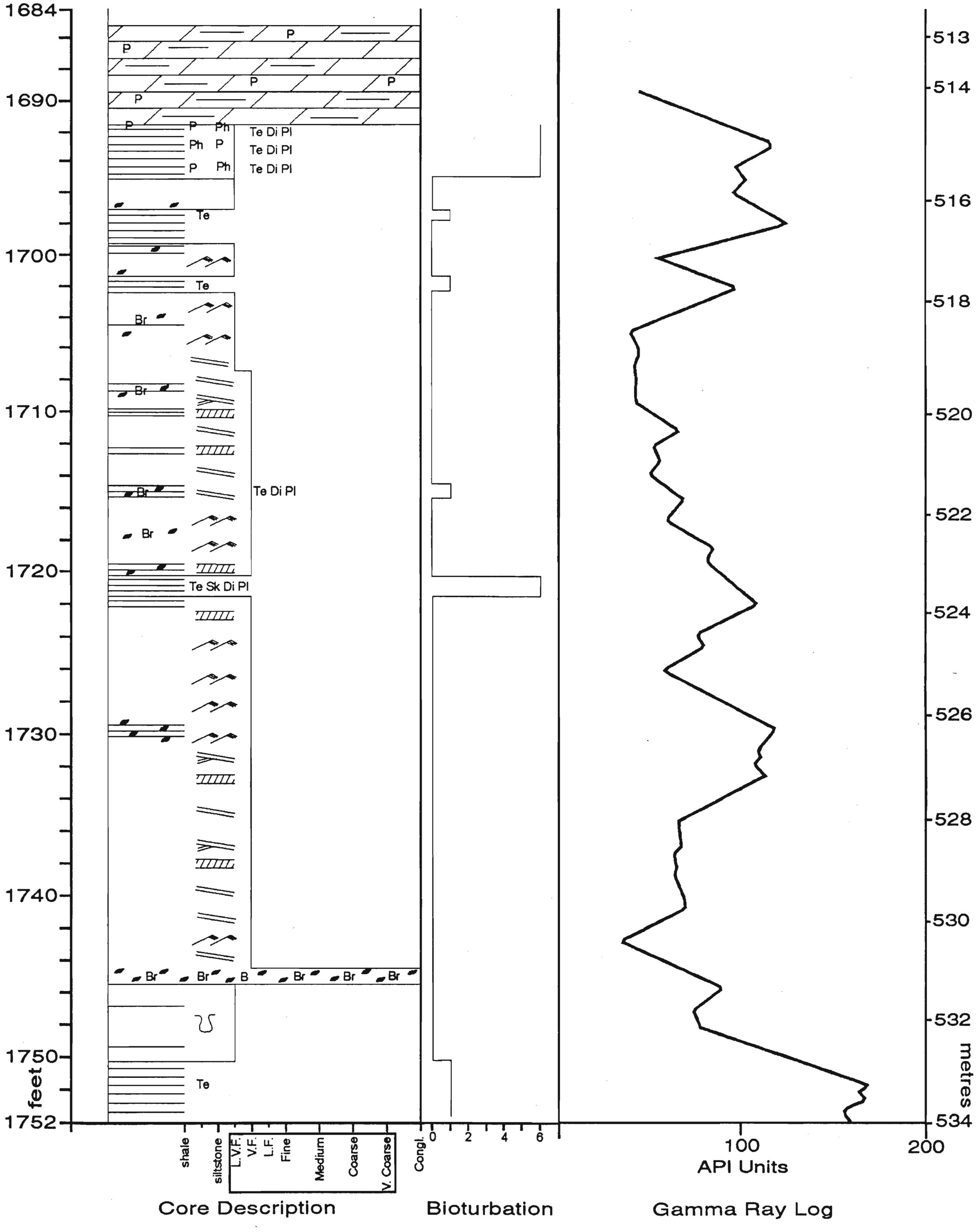


Well Name: Consumers 13226
Block Number: 155-A

Latitude: 42 24' 23.54" N
Longitude: 80 40' 05.63" W

Cored Interval: 1685 - 1751.5 ft.
513.6 - 533.9 m

K.B. Elev.: 619 ft. 188.7 m
Pet. Res. Core No.: #442

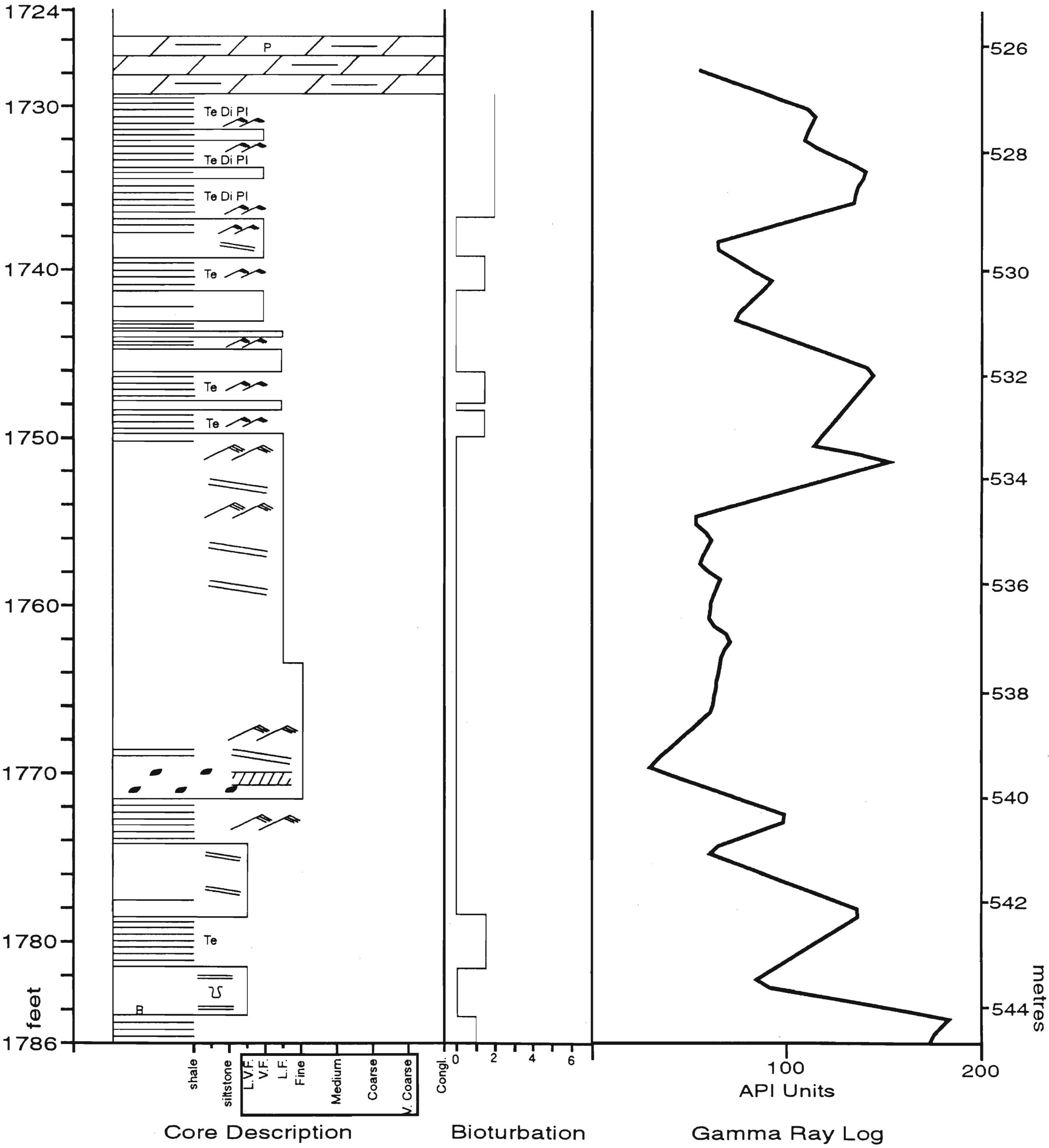


Well Name: Consumers 13202
Block Number: 155-F

Latitude: 42 23' 13.12" N
Longitude: 80 44' 34.99" W

Cored Interval: 1726 - 1786 ft.
526.1 - 544.4 m

K.B. Elev.: 617 ft. 188.1 m
Pet. Res. Core No.: #333

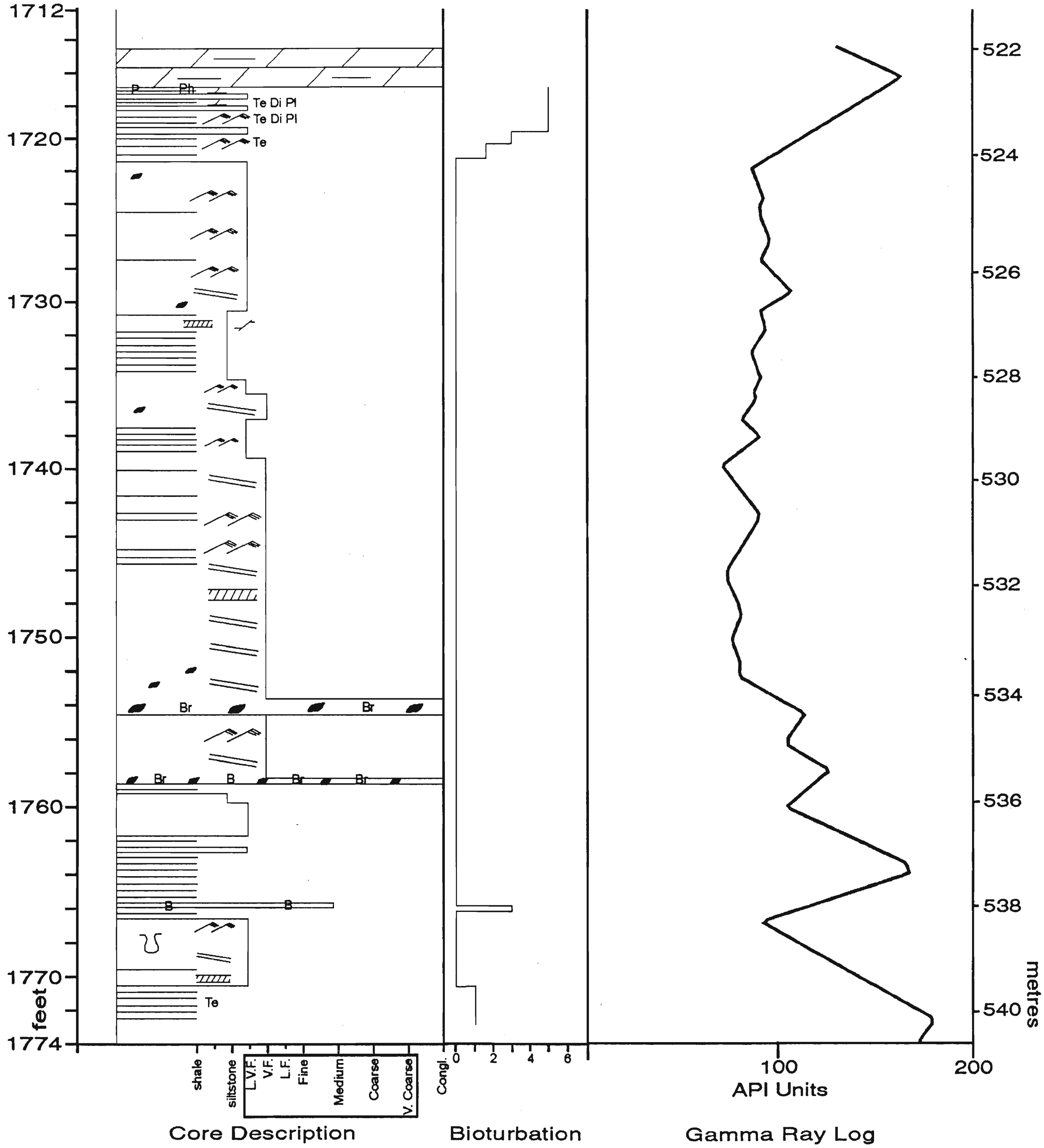


Well Name: Consumers 13234
Block Number: 155-I

Latitude: 42 23' 54.73" N
Longitude: 80 41' 19.20" W

Cored Interval: 1714 - 1772.5 ft.
522.4 - 540.3 m

K.B. Elev.: 619 ft. 188.7 m
Pet. Res. Core No.: #308

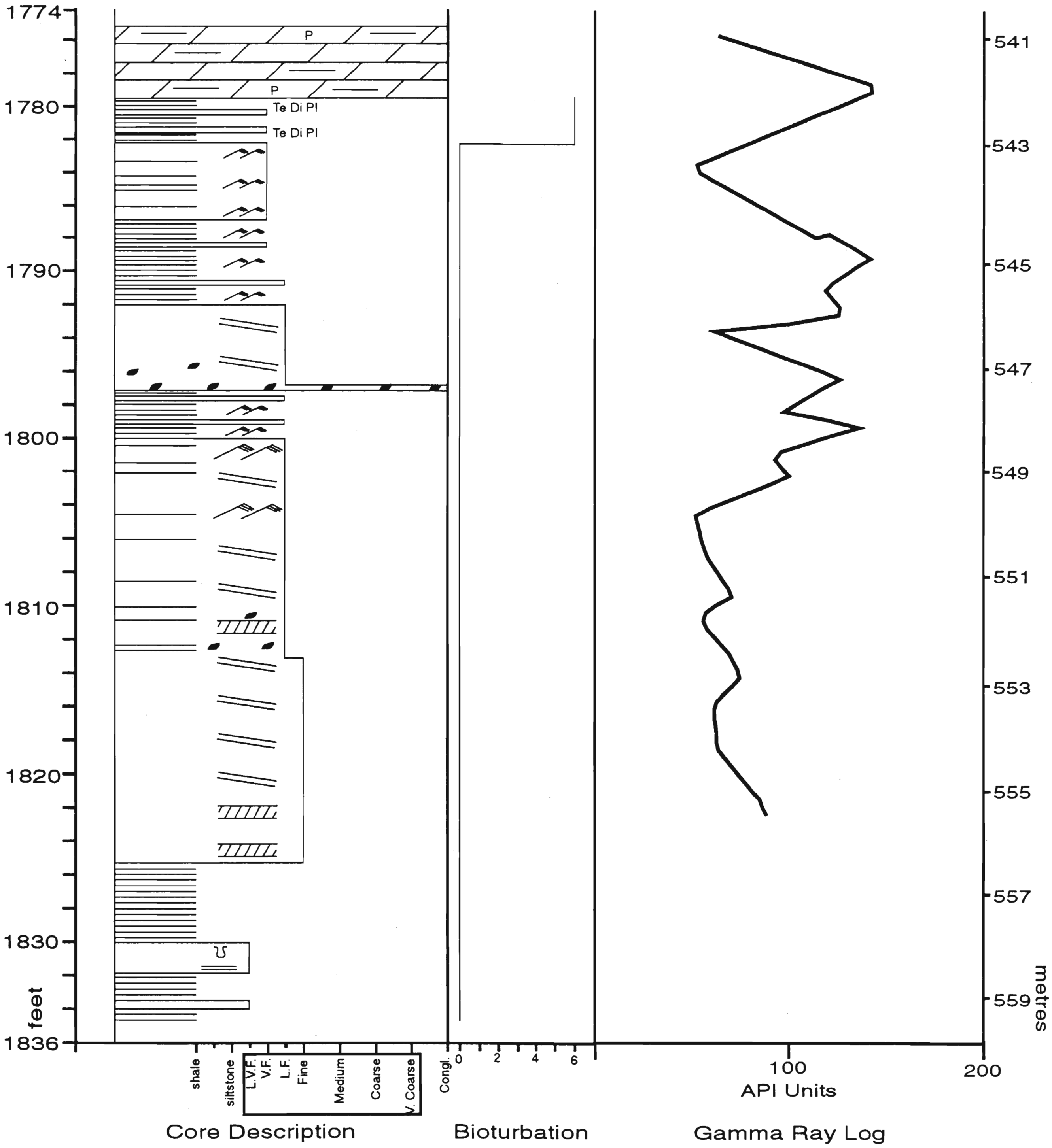


Well Name: Consumers 13222
Block Number: 155-P

Latitude: 42 21' 31.66" N
Longitude: 80 44' 48.55" W

Cored Interval: 1775 - 1835 ft.
541.0 - 559.3 m

K.B. Elev.: 617 ft. 188.1 m
Pet. Res. Core No.: #180

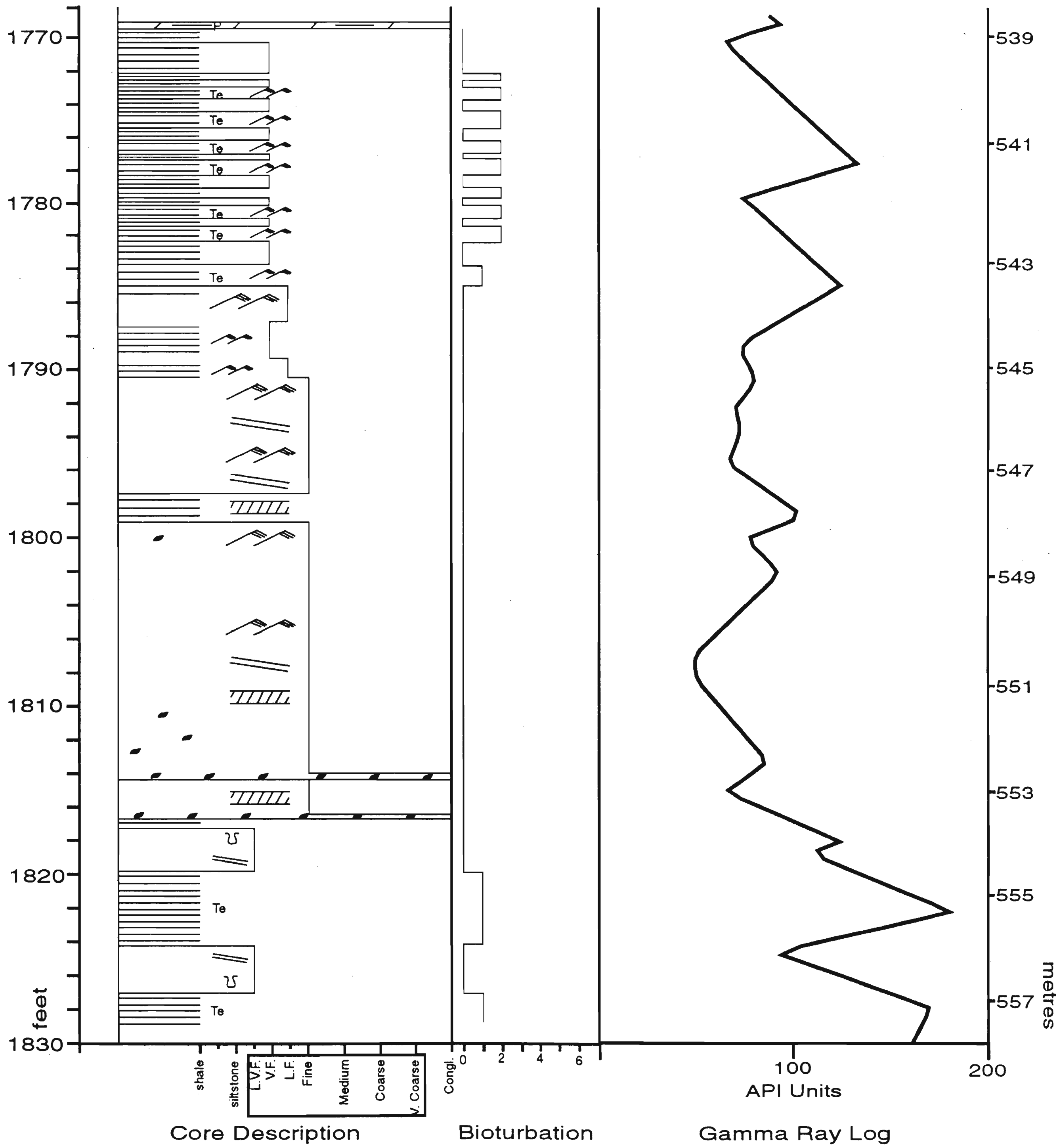


Well Name: Consumers 13298
Block Number: 155-P

Latitude: 42 21' 55.00" N
Longitude: 80 44' 17.36" W

Cored Interval: 1769 - 1829 ft.
539.2 - 557.5 m

K.B. Elev.: 619 ft. 188.7 m
Pet. Res. Core No.: #368

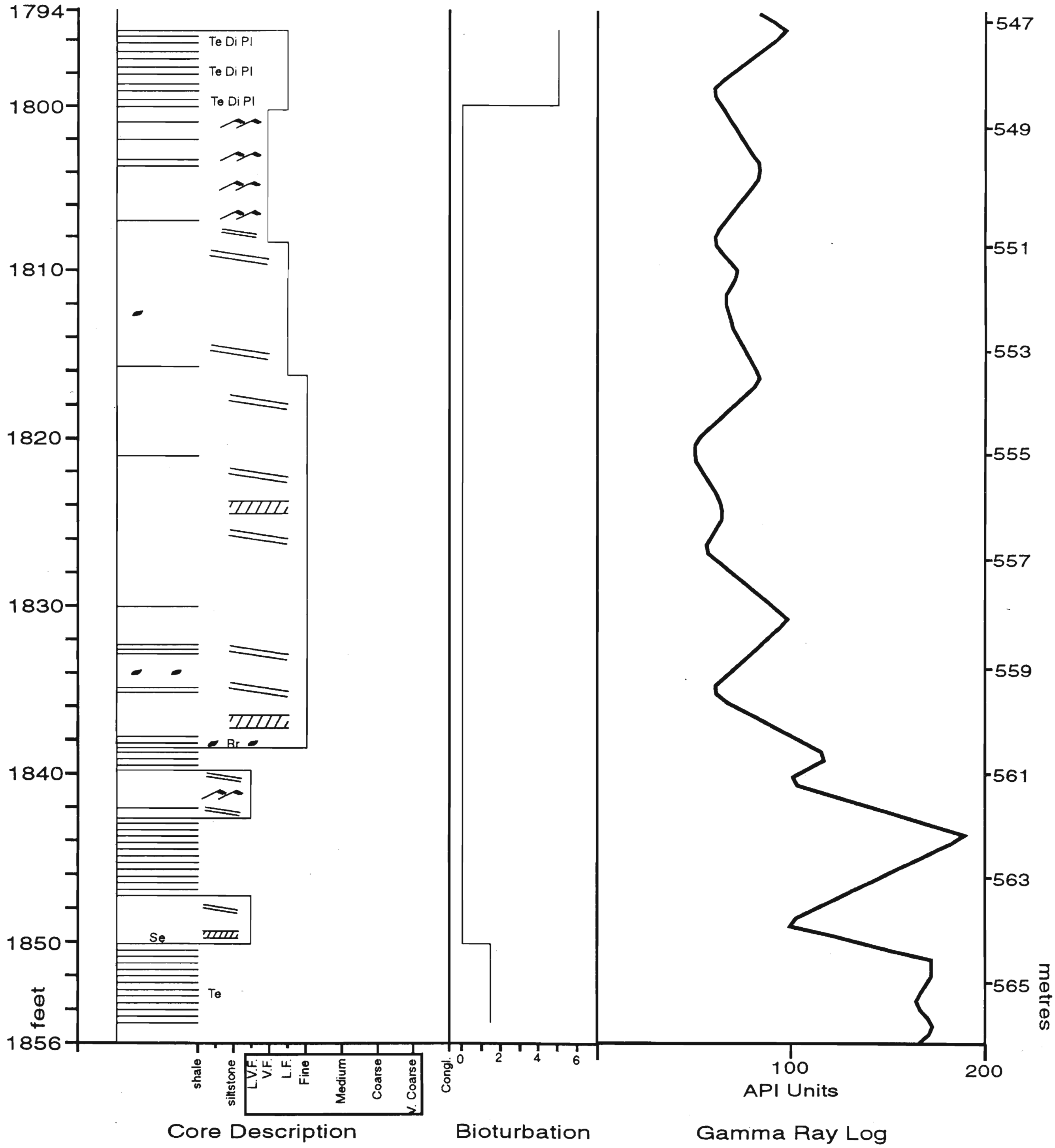


Well Name: Consumers 13299
Block Number: 155-P

Latitude: 42 21' 05.33" N
Longitude: 80 44' 03.19" W

Cored Interval: 1795 - 1855 ft.
547.1 - 565.4 m

K.B. Elev.: 616 ft. 187.8 m
Pet. Res. Core No.: #519

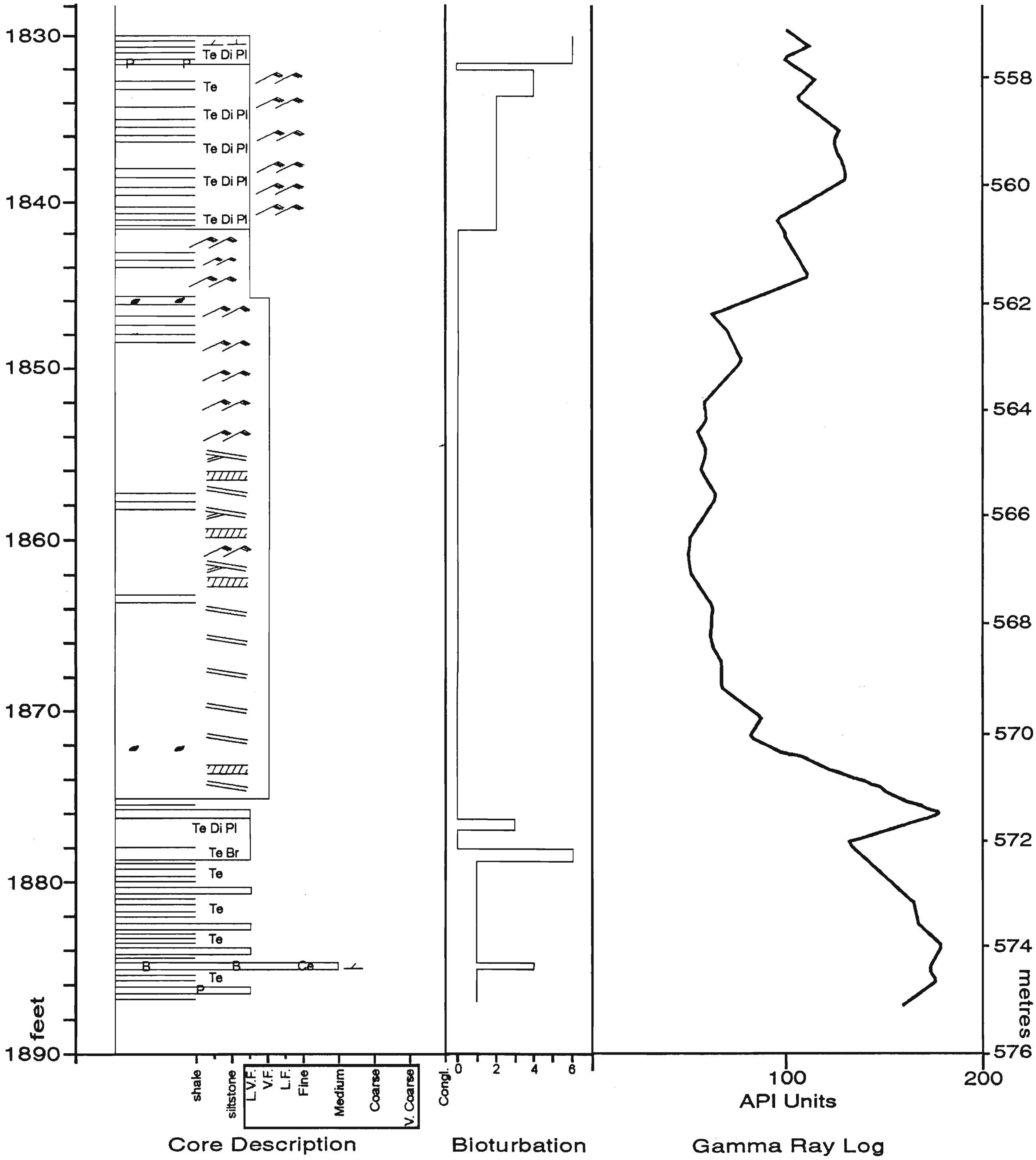


Well Name: Consumers 13232
Block Number: 155-W

Latitude: 42 20' 20.01" N
Longitude: 80 42' 18.58" W

Cored Interval: 1830 - 1888.5 ft.
557.8 - 575.6 m

K.B. Elev.: 617 ft. 188.1 m
Pet. Res. Core No.: #405

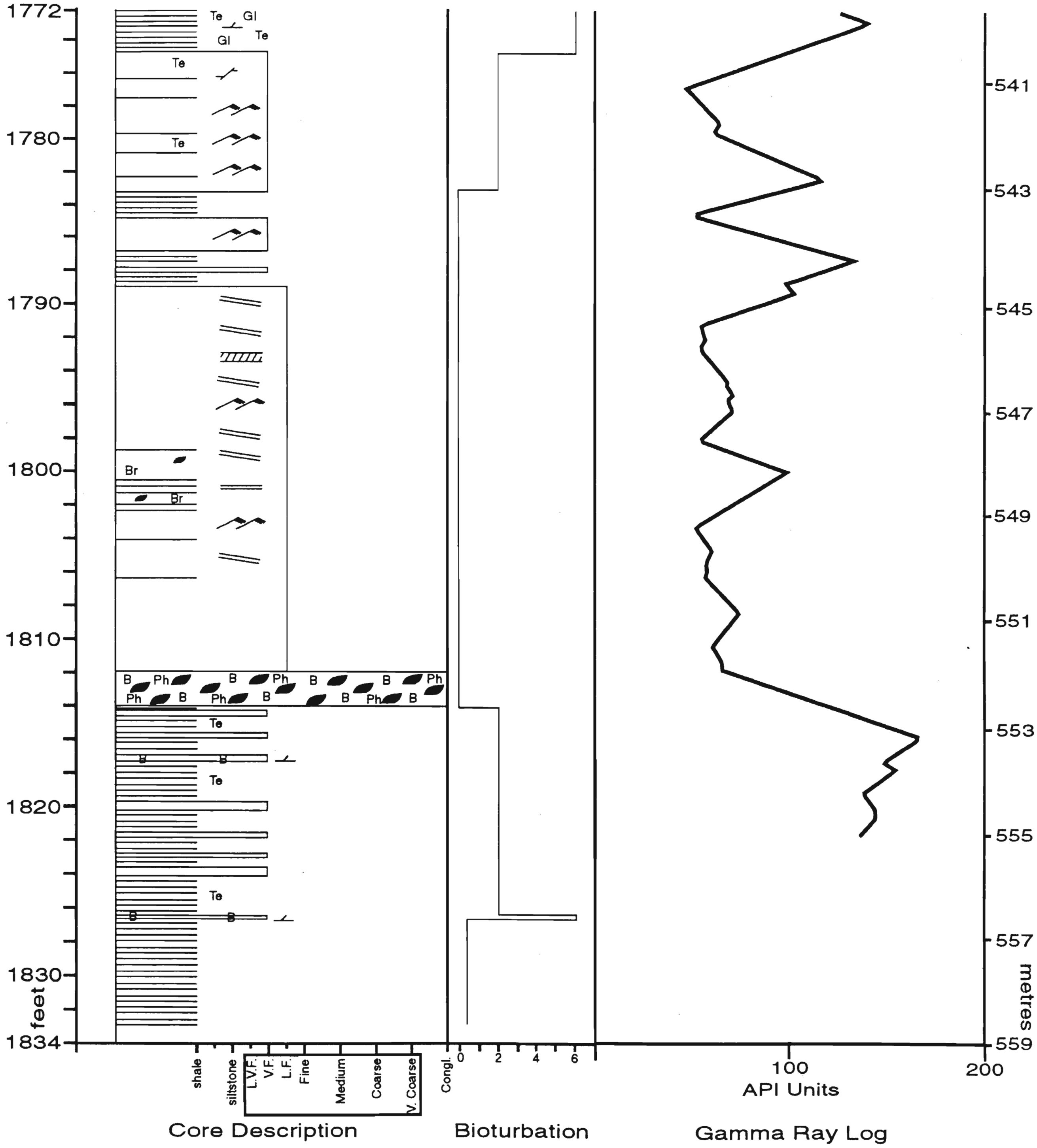


Well Name: Consumers 13204
Block Number: 156-L

Latitude: 42 22' 35.26" N
Longitude: 80 46' 36.14" W

Cored Interval: 1772 - 1833 ft.
540.1 - 558.7 m

K.B. Elev.: 618 ft. 188.4 m
Pet. Res. Core No.: #404

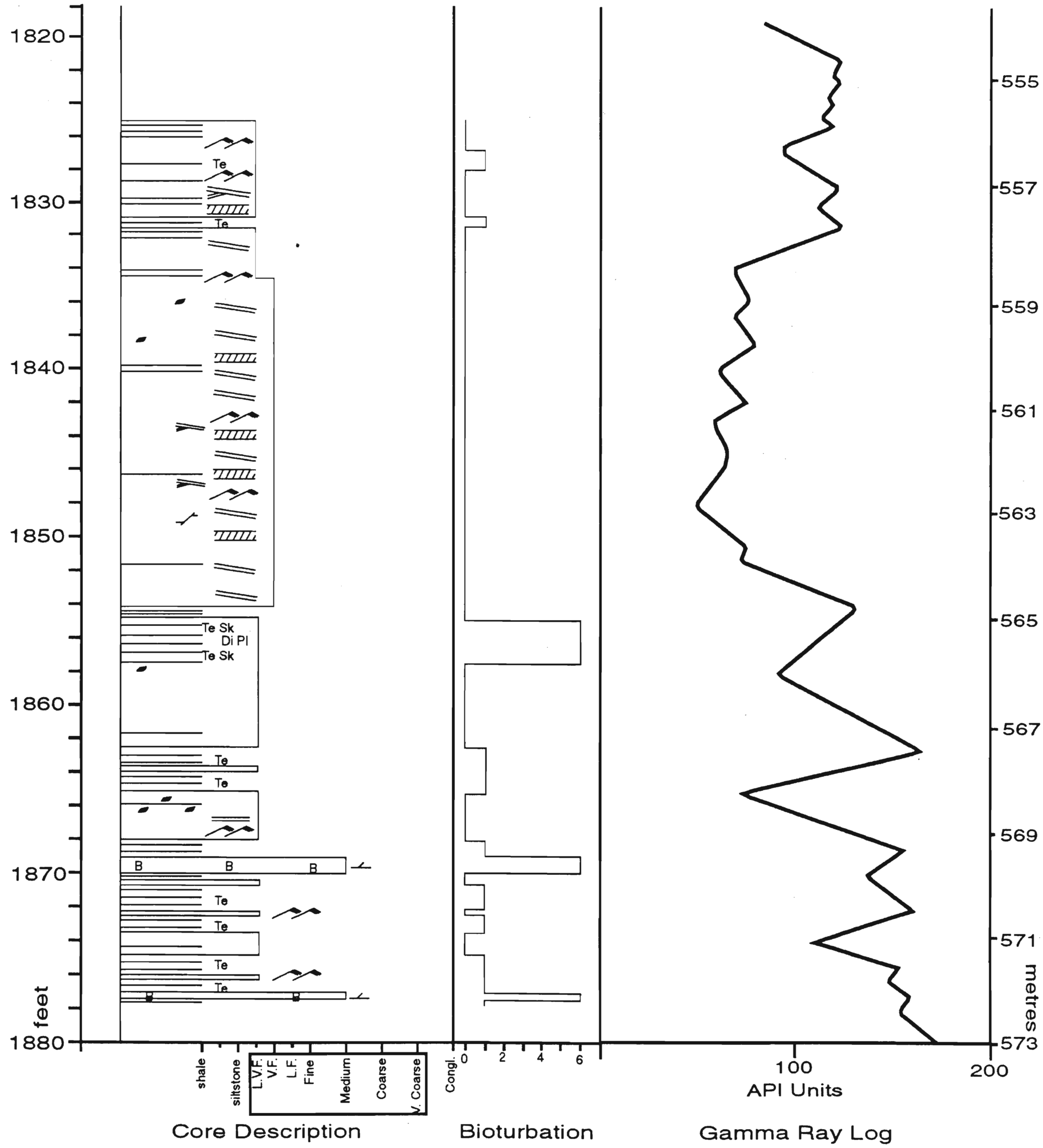


Well Name: Consumers 13240
Block Number: 156-X

Latitude: 42 20' 19.36" N
Longitude: 80 48' 08.51" W

Cored Interval: 1825 - 1877.7 ft.
556.3 - 572.3 m

K.B. Elev.: 619 ft. 188.7 m
Pet. Res. Core No.: #416

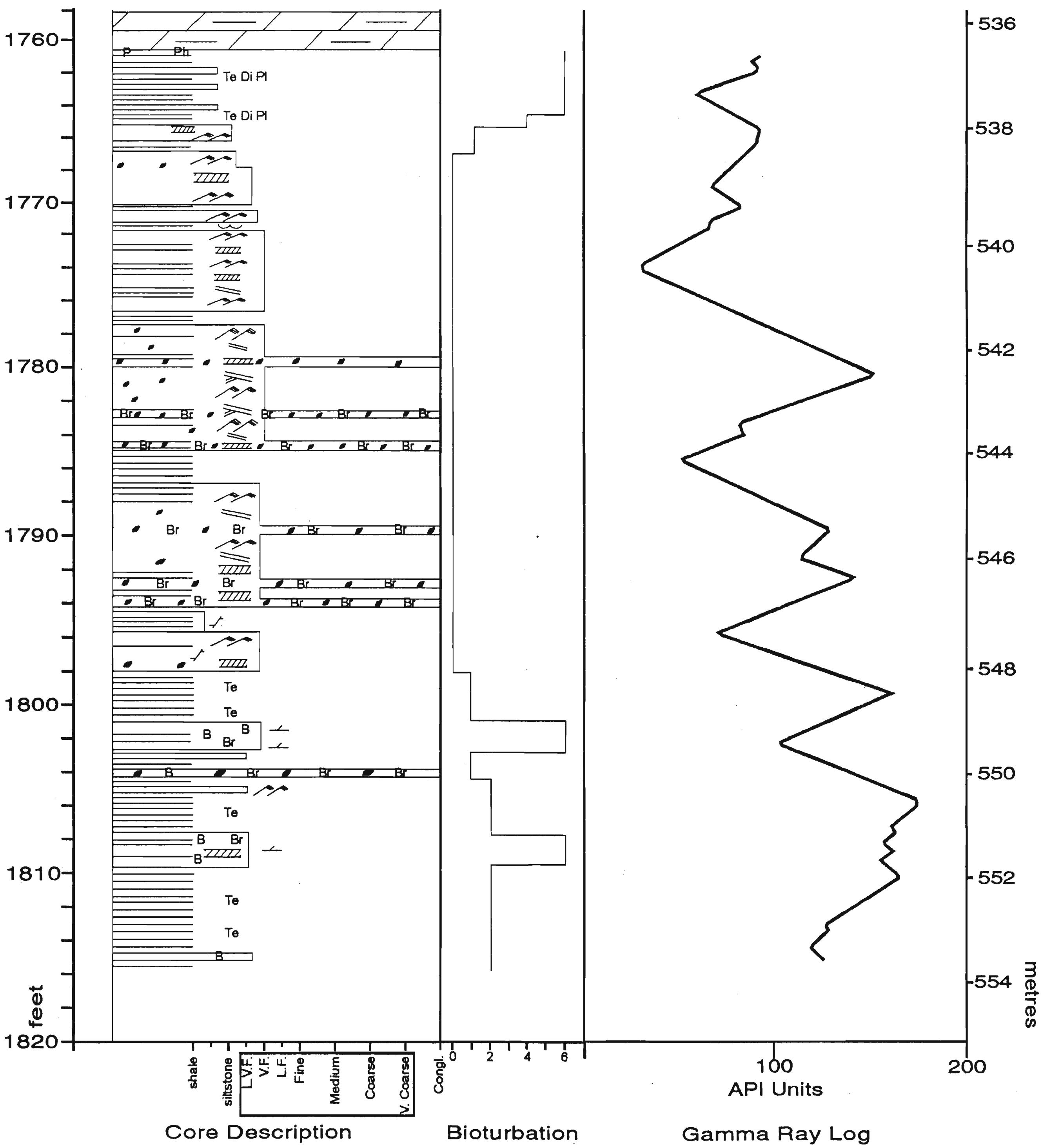


Well Name: Consumers 13164
Block Number: 157-M

Latitude: 42 22' 48.83" N
Longitude: 80 52' 41.82" W

Cored Interval: 1759 - 1815 ft.
536.1 - 553.2 m

K.B. Elev.: 615 ft. 187.5 m
Pet. Res. Core No.: #337

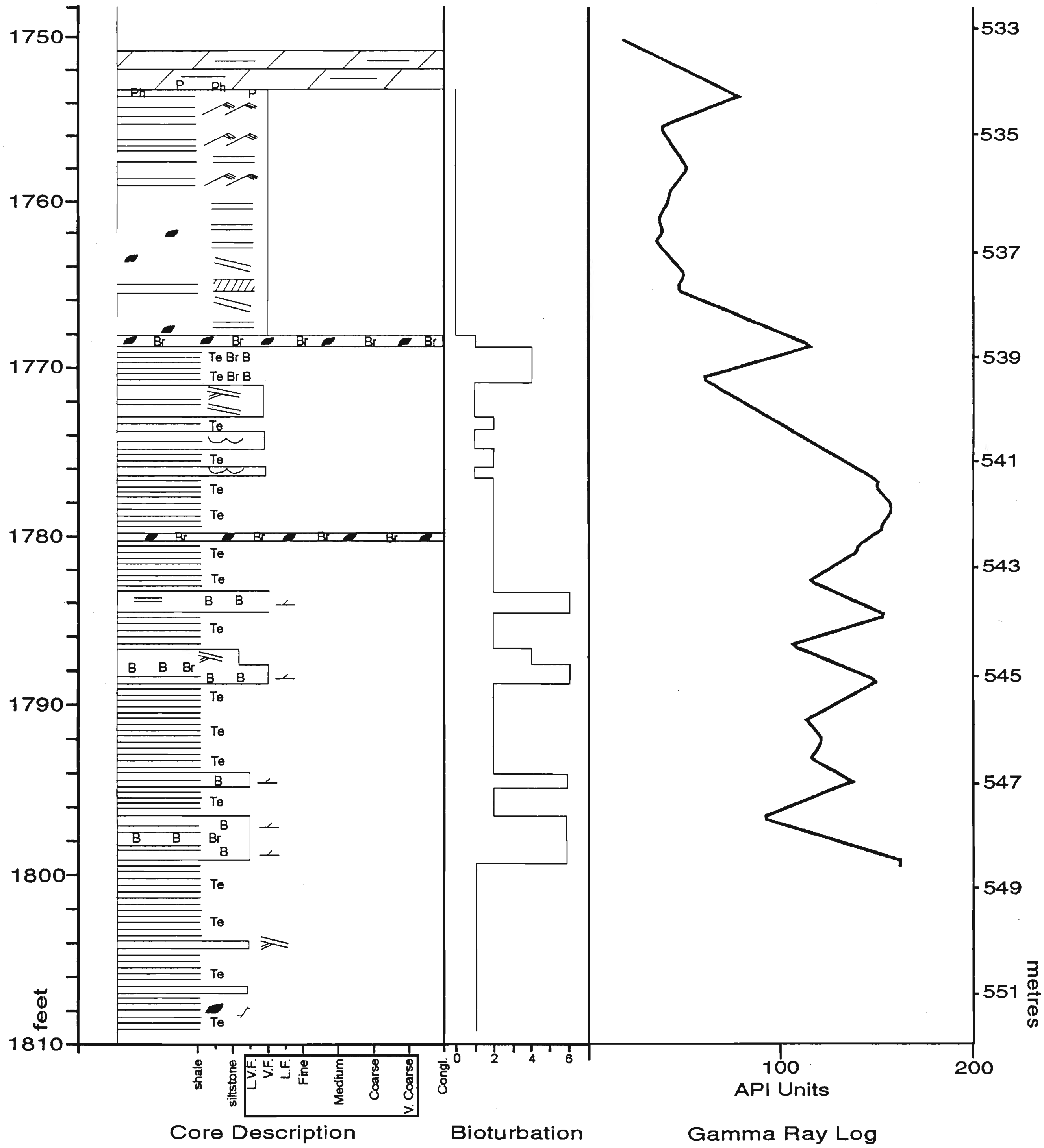


Well Name: Consumers 13275
Block Number: 158-D

Latitude: 42 24' 32.16" N
Longitude: 80 58' 48.02" W

Cored Interval: 1750 - 1809 ft.
533.4 - 551.4 m

K.B. Elev.: 618 ft. 188.4 m
Pet. Res. Core No.: #351

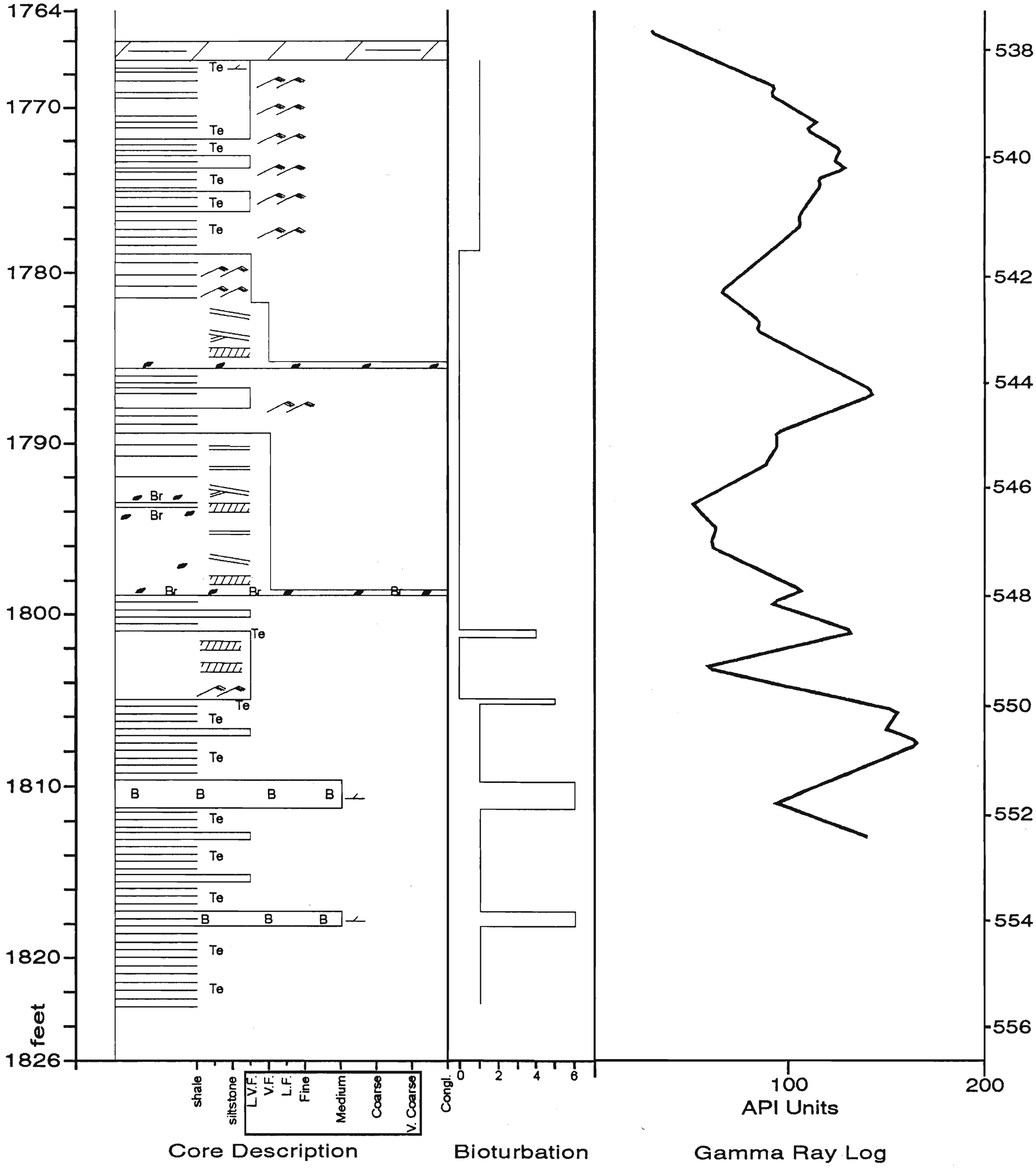


Well Name: Consumers 13273
Block Number: 158-K

Latitude: 42 22' 52.85" N
Longitude: 80 55' 00.95" W

Cored Interval: 1766 - 1823 ft.
538.3 - 555.7 m

K.B. Elev.: 617 ft. 188.1 m
Pet. Res. Core No.: #305

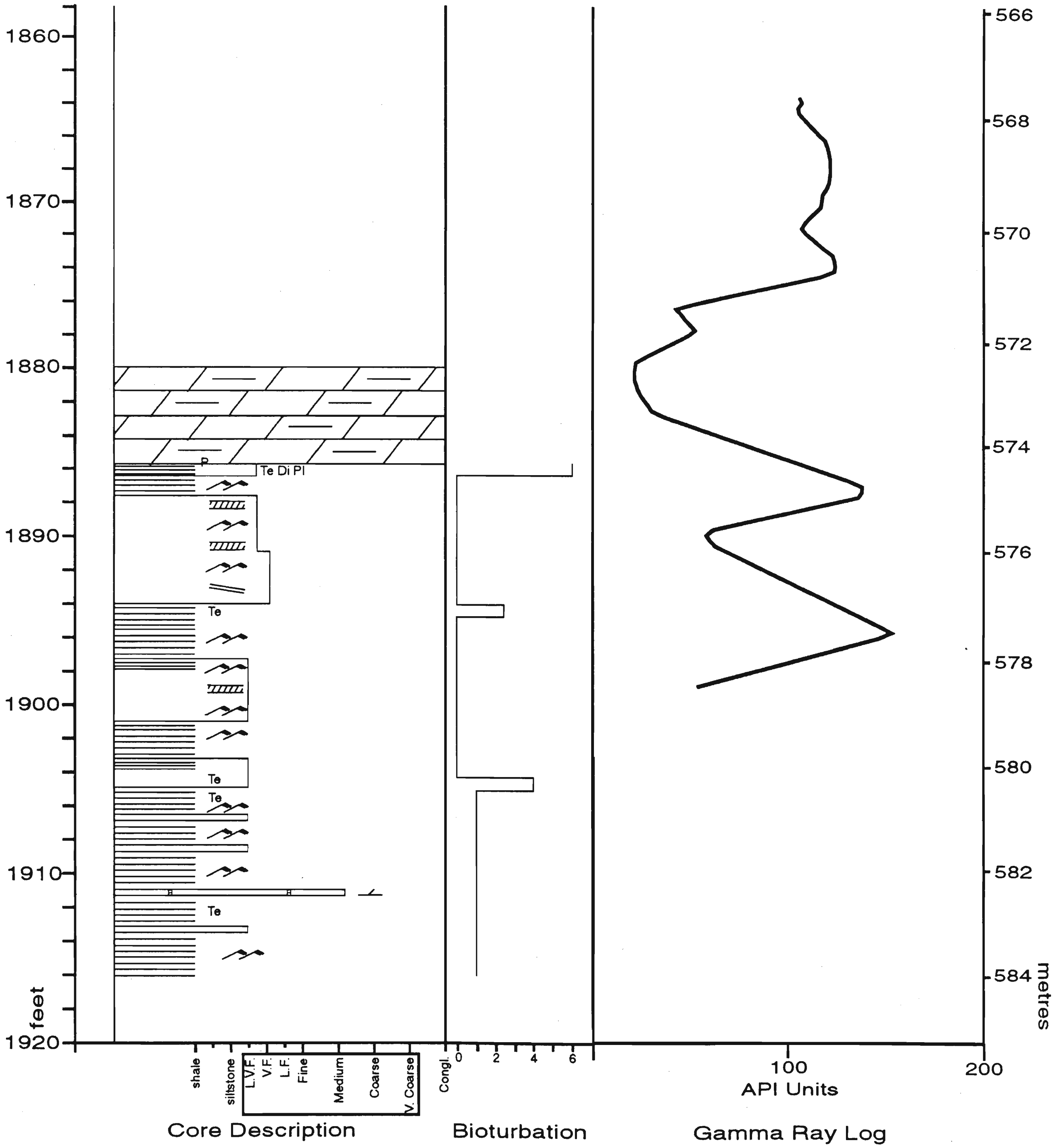


Well Name: Anschutz #4
Block Number: 162-T

Latitude: 42 21' 11.01" N
Longitude: 81 15' 14.32" W

Cored Interval: 1856 - 1916 ft. (1880-1916' described)
565.7 - 584.0 m

K.B. Elev.: 597 ft. 182.0 m
Pet. Res. Core No.: #694

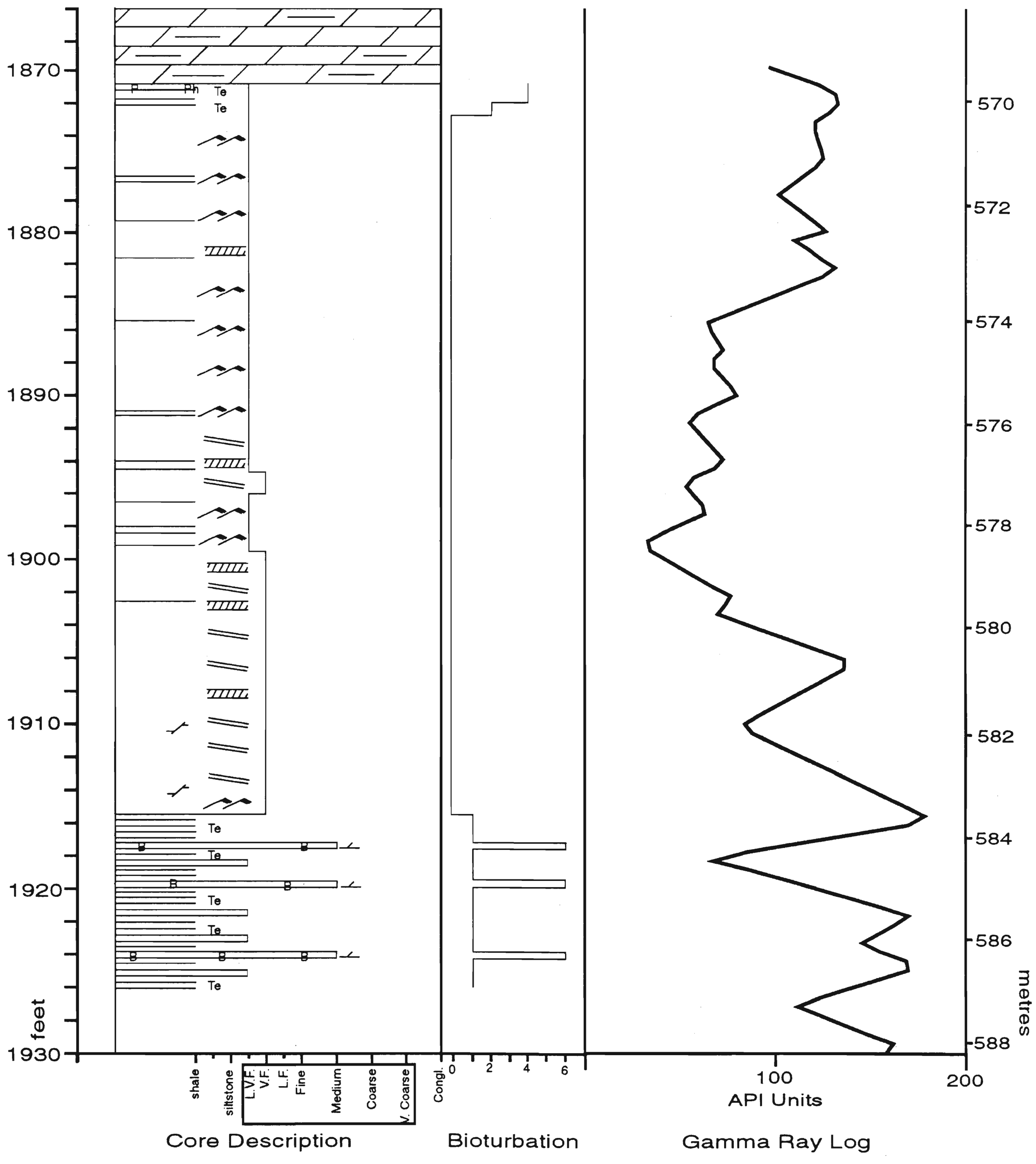


Well Name: Consumers 13171
Block Number: 185-C

Latitude: 42 19' 11.29" N
Longitude: 80 52' 22.42" W

Cored Interval: 1866 - 1926 ft.
568.8 - 587.1 m

K.B. Elev.: 619 ft. 188.7 m
Pet. Res. Core No.: #326

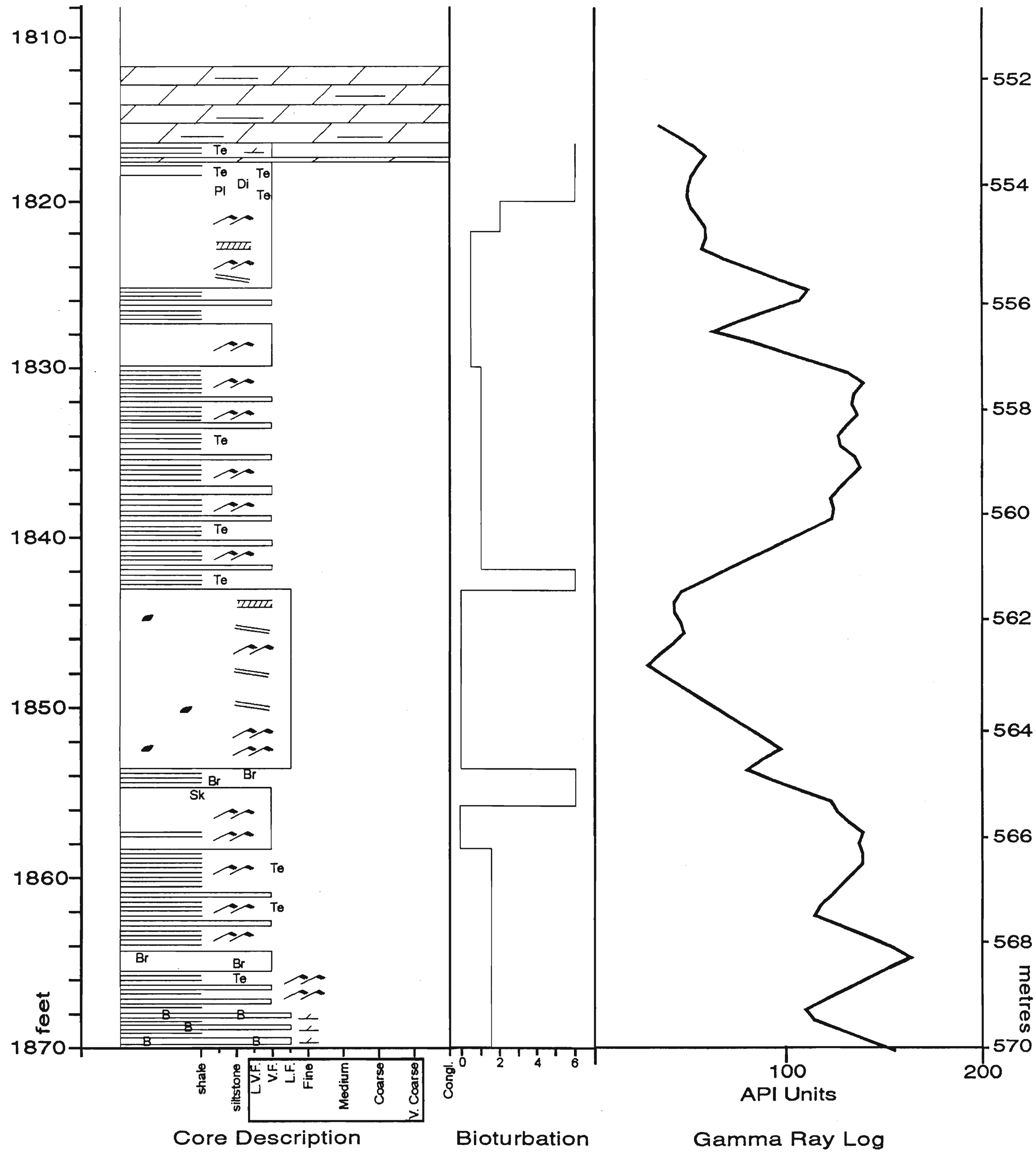


Well Name: Consumers 13747
Block Number: 186-J

Latitude: 42 18' 54.99" N
Longitude: 80 45' 08.71" W

Cored Interval: 1811 - 1870 ft.
552.0 - 570.0 m

K.B. Elev.: 597 ft. 181.8 m
Pet. Res. Core No.: #768

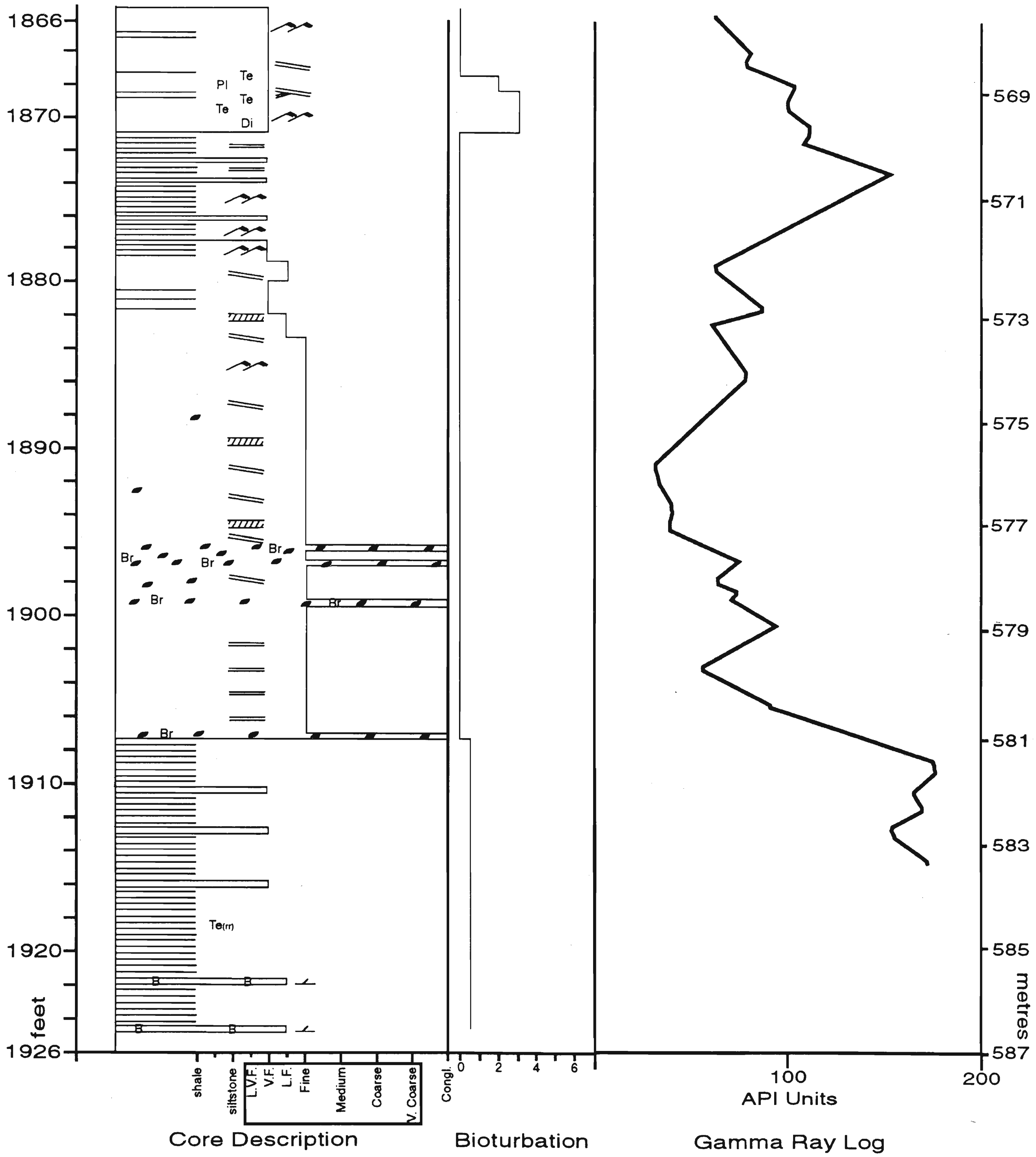


Well Name: Consumers Pan Am 13041
Block Number: 187-D

Latitude: 42 19' 31.0" N
Longitude: 80 43' 16.2" W

Cored Interval: 1865 - 1925 ft.
568.5 - 586.7 m

K.B. Elev.: 612 ft. 186.5 m
Pet. Res. Core No.: #810

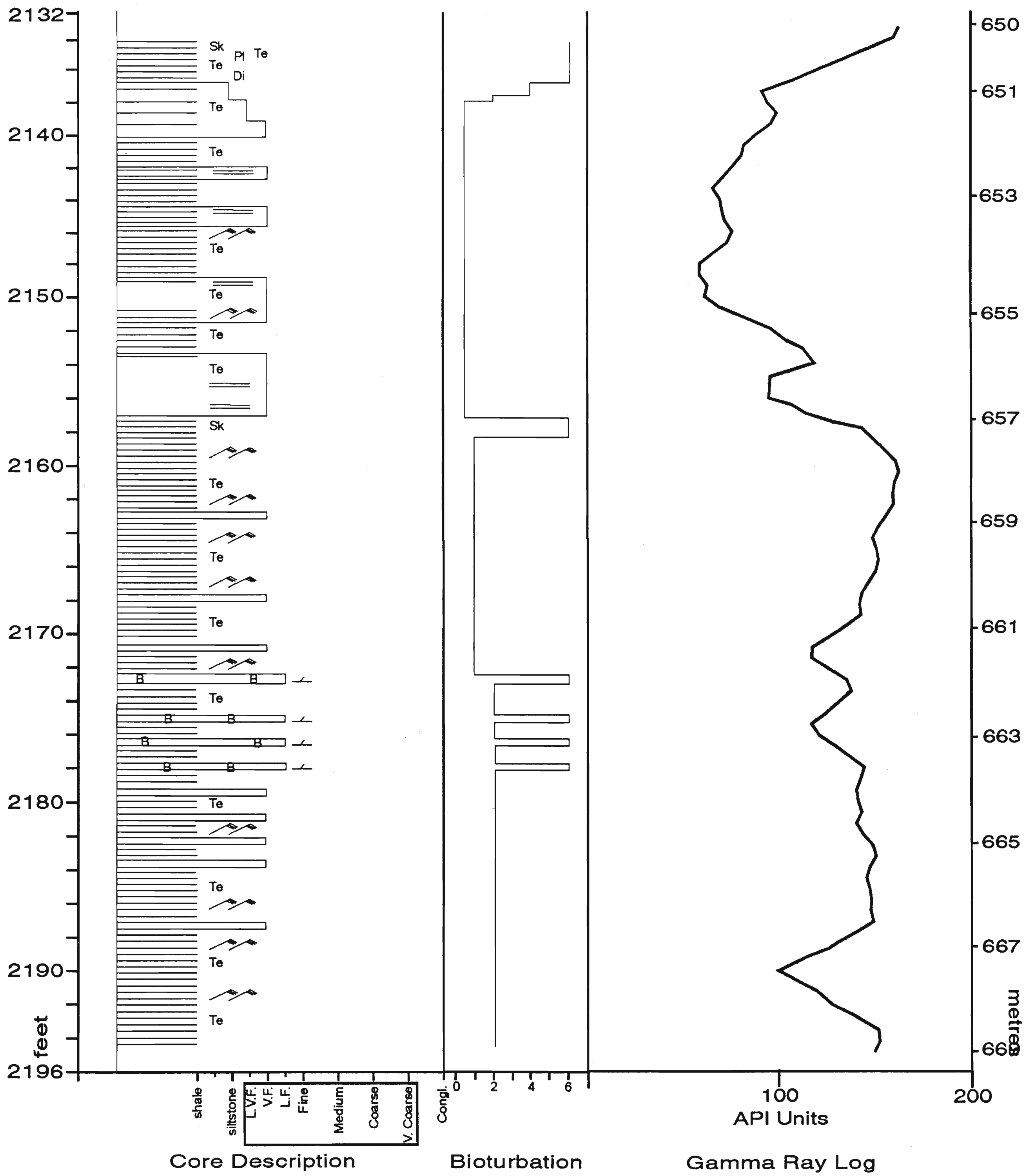


Well Name: Consumers 13755
Block Number: 220-W

Latitude: 42 10' 26.91" N
Longitude: 81 22' 17.55" W

Cored Interval: 2134 - 2194 ft.
650.5 - 668.8 m

K.B. Elev.: 595 ft. 181.2 m
Pet. Res. Core No.: #766

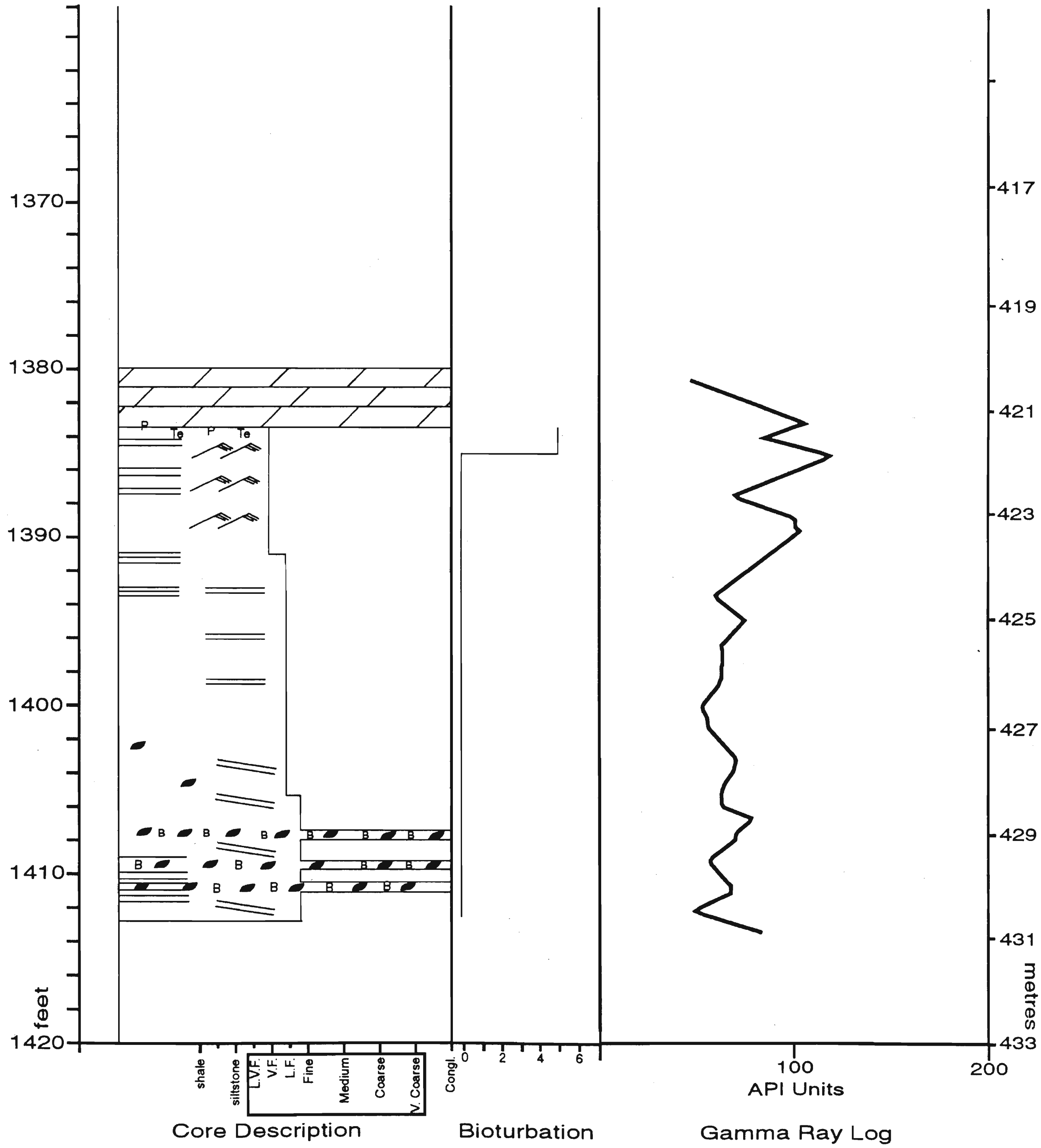


Well Name: Shawnee UBR S. Walsingham
County: Norfolk
Tract/Lot/Conc: 3-4-A

Latitude: 42 35' 46" N
Longitude: 80 32' 13" W

Cored Interval: 1380 - 1411 ft.
420.6 - 430.4 m

K.B. Elev.: 643 ft. 196.0 m
Pet. Res. Core No.: #115

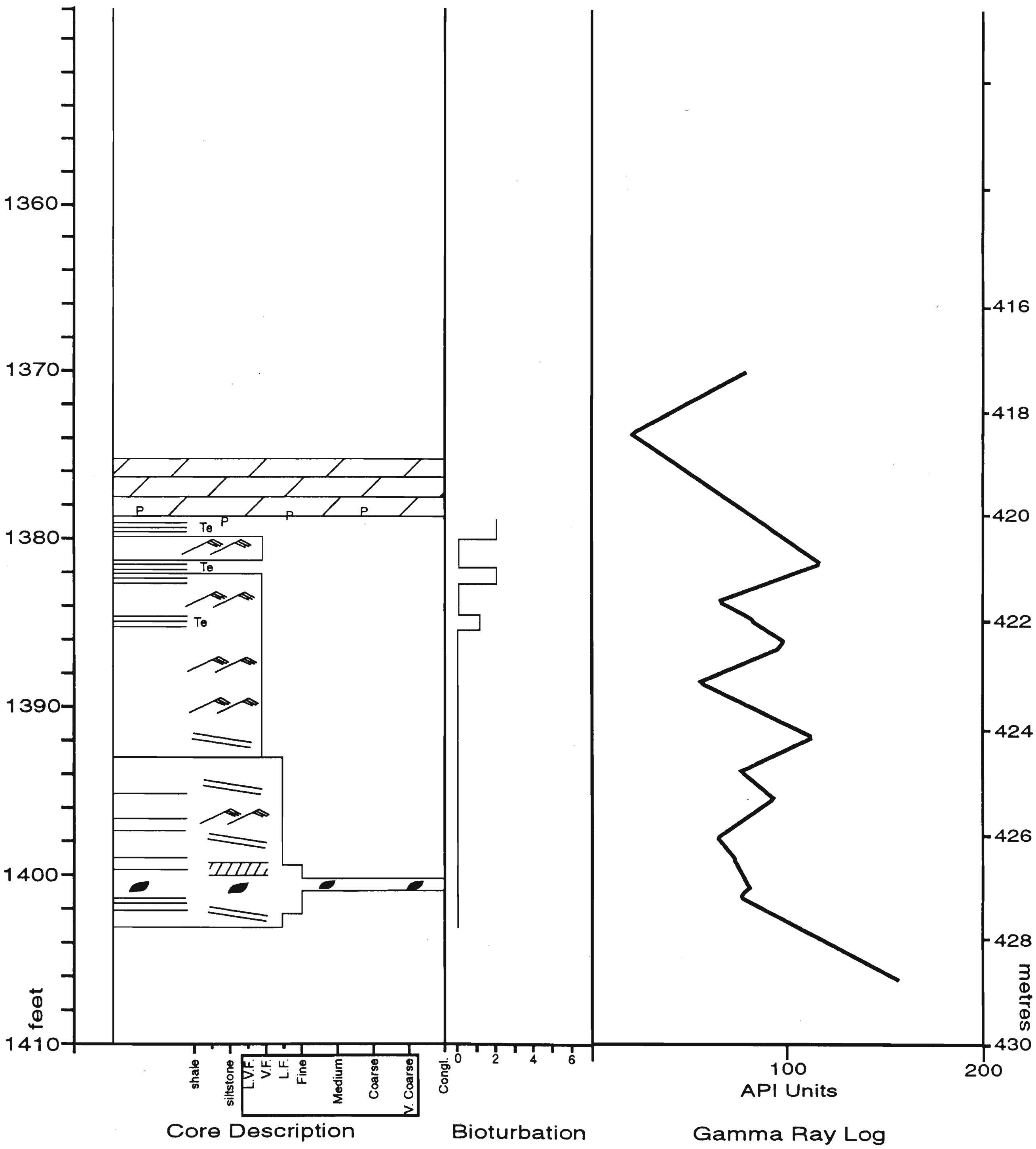


Well Name: Shawnee UBR S. Walsingham
County: Norfolk
Tract/Lot/Conc: 3-5-I

Latitude: 42 36' 34" N
Longitude: 80 32' 19" W

Cored Interval: 1375 - 1403 ft.
419.1 - 427.6 m

K.B. Elev.: 653 ft. 199.0 m
Pet. Res. Core No.: #104

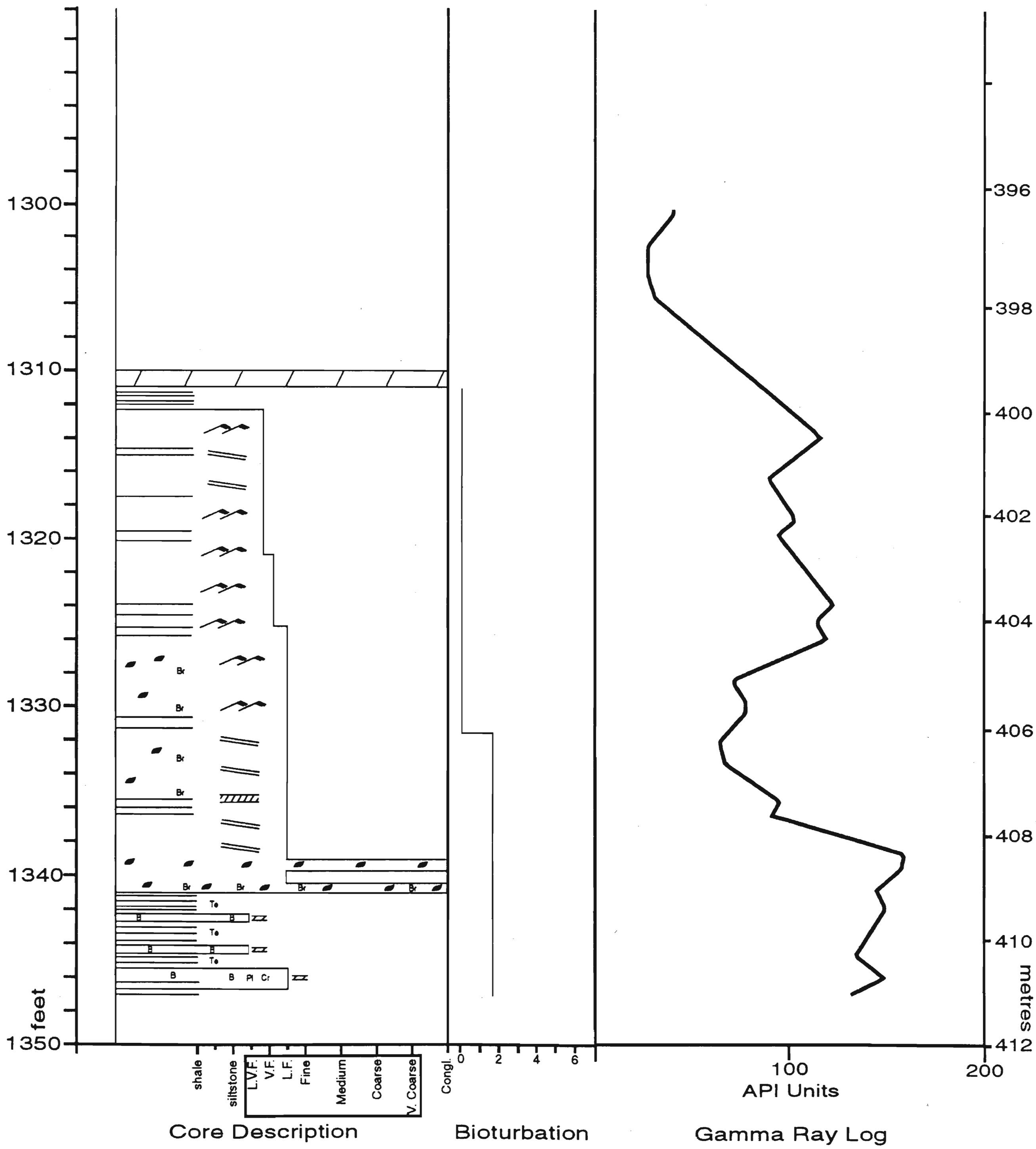


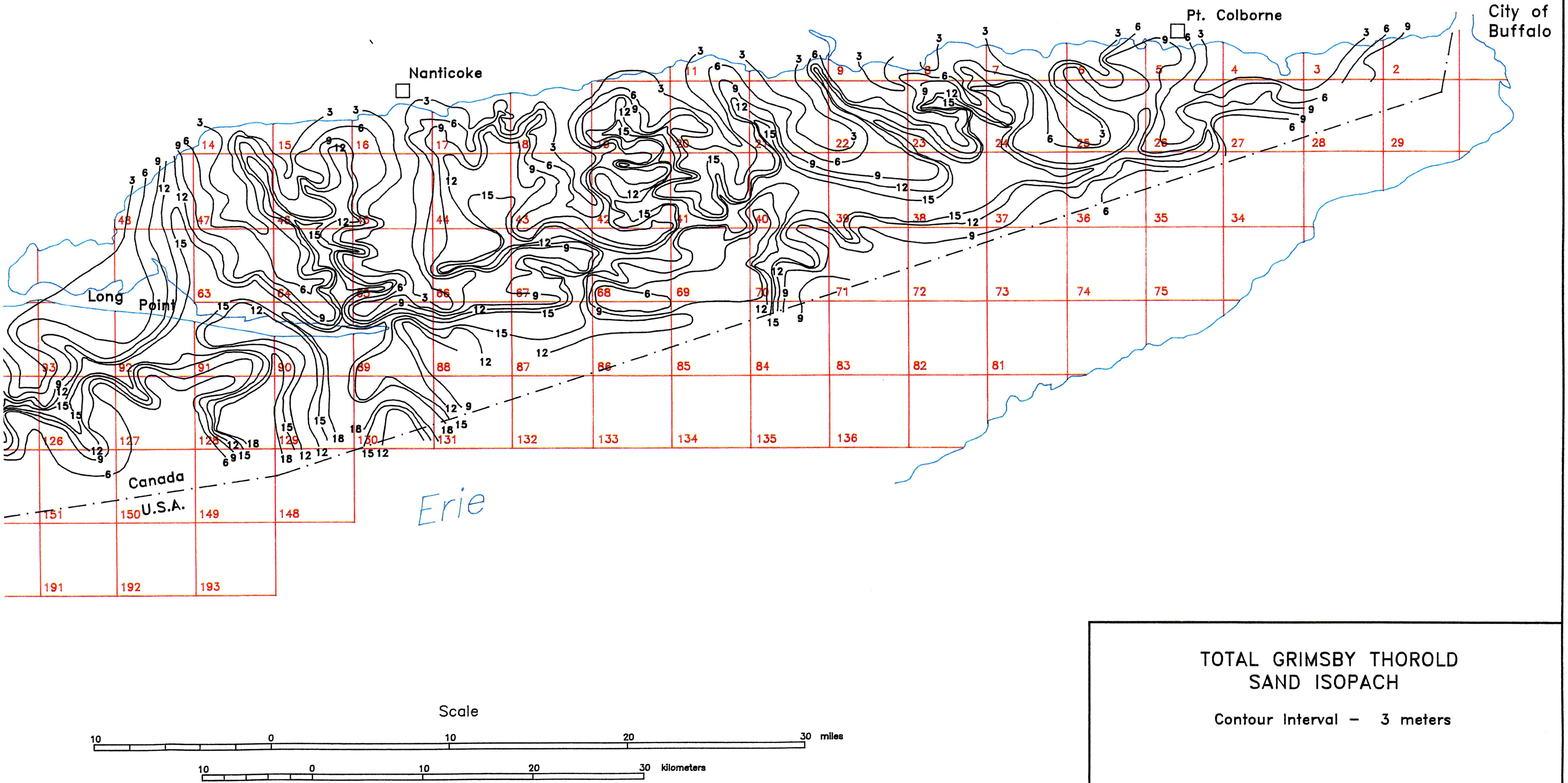
Well Name: Shawnee UBR N. Walsingham
Block Number: Norfolk County 1-10-VII

Latitude: 42 41' 21" N
Longitude: 80 33' 36" W

Cored Interval: 1310 - 1347 ft.
399.3 - 410.6 m

K.B. Elev.: 689 ft. 210.1 m
Pet. Res. Core No.: #103





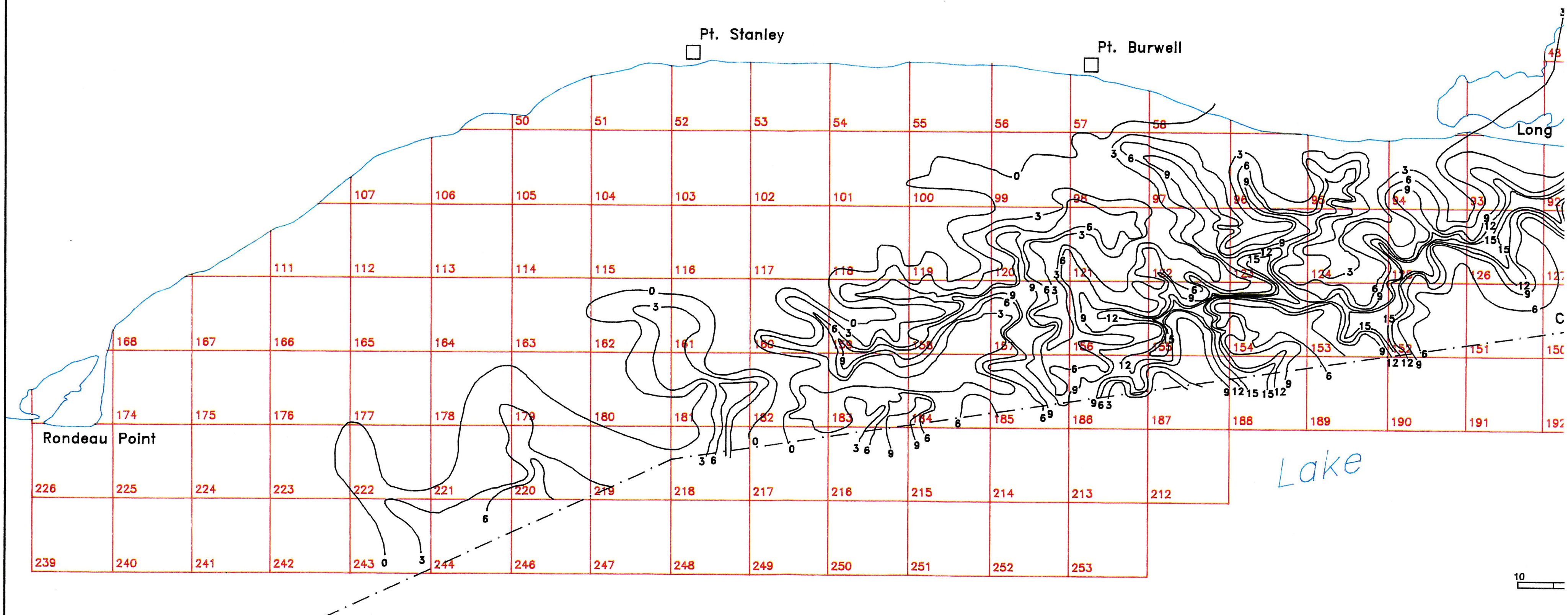
TOTAL GRIMSBY THOROLD
SAND ISOPACH

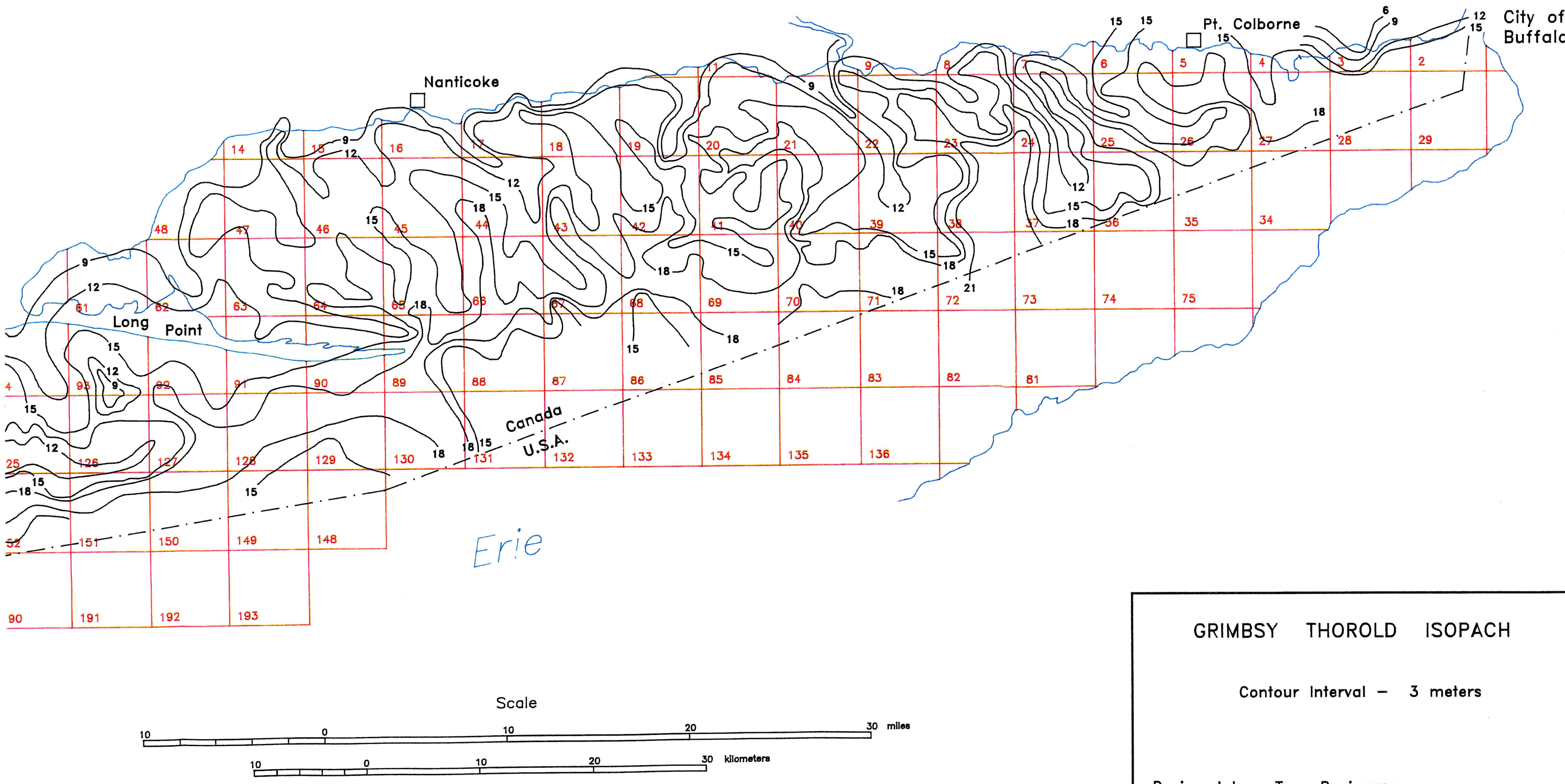
Contour Interval – 3 meters

Designed by: Tony Benincasa

Dept. Earth Sciences
Brock University

MAP 3


Pt. Stanley
Pt. Burwell
Long
Rondeau Point
Lake
10



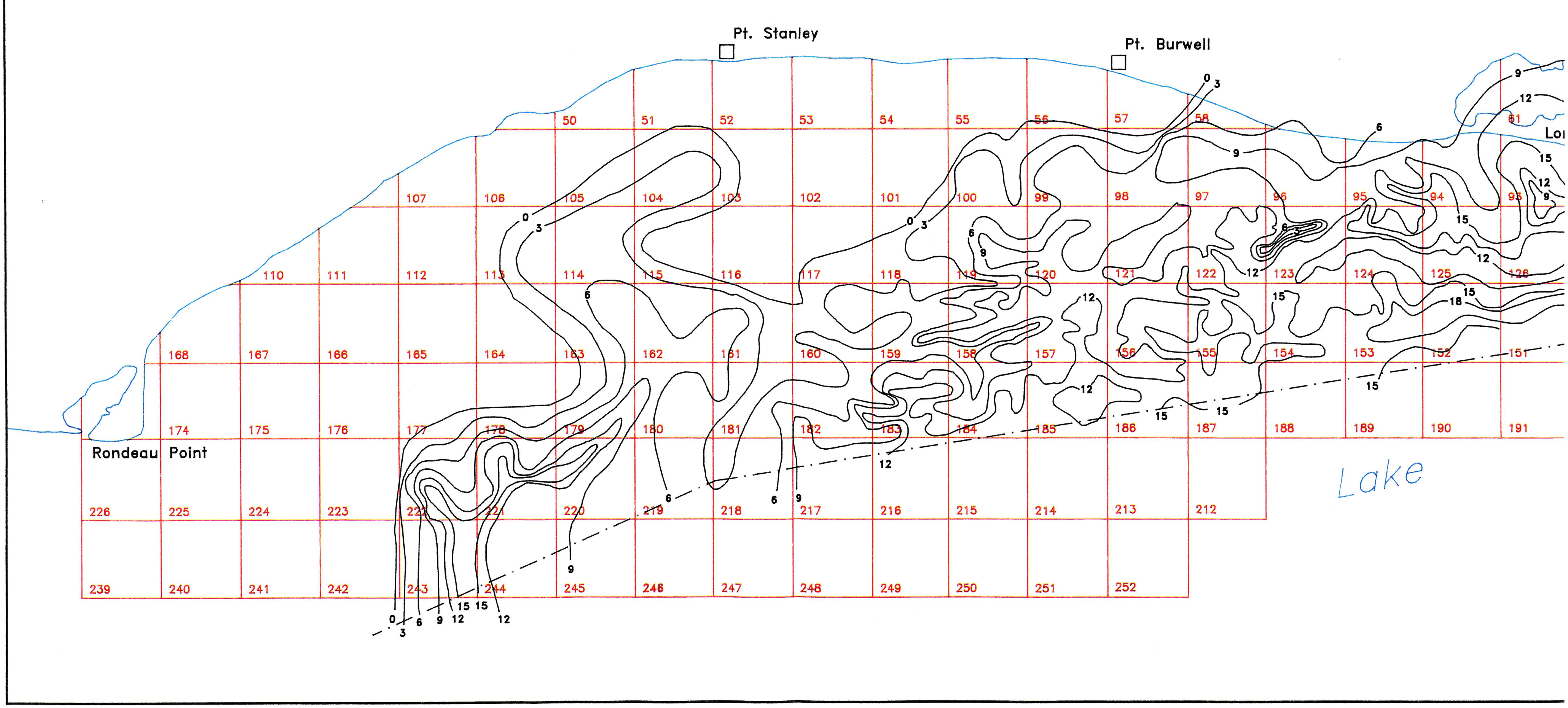
GRIMBSY THOROLD ISOPACH

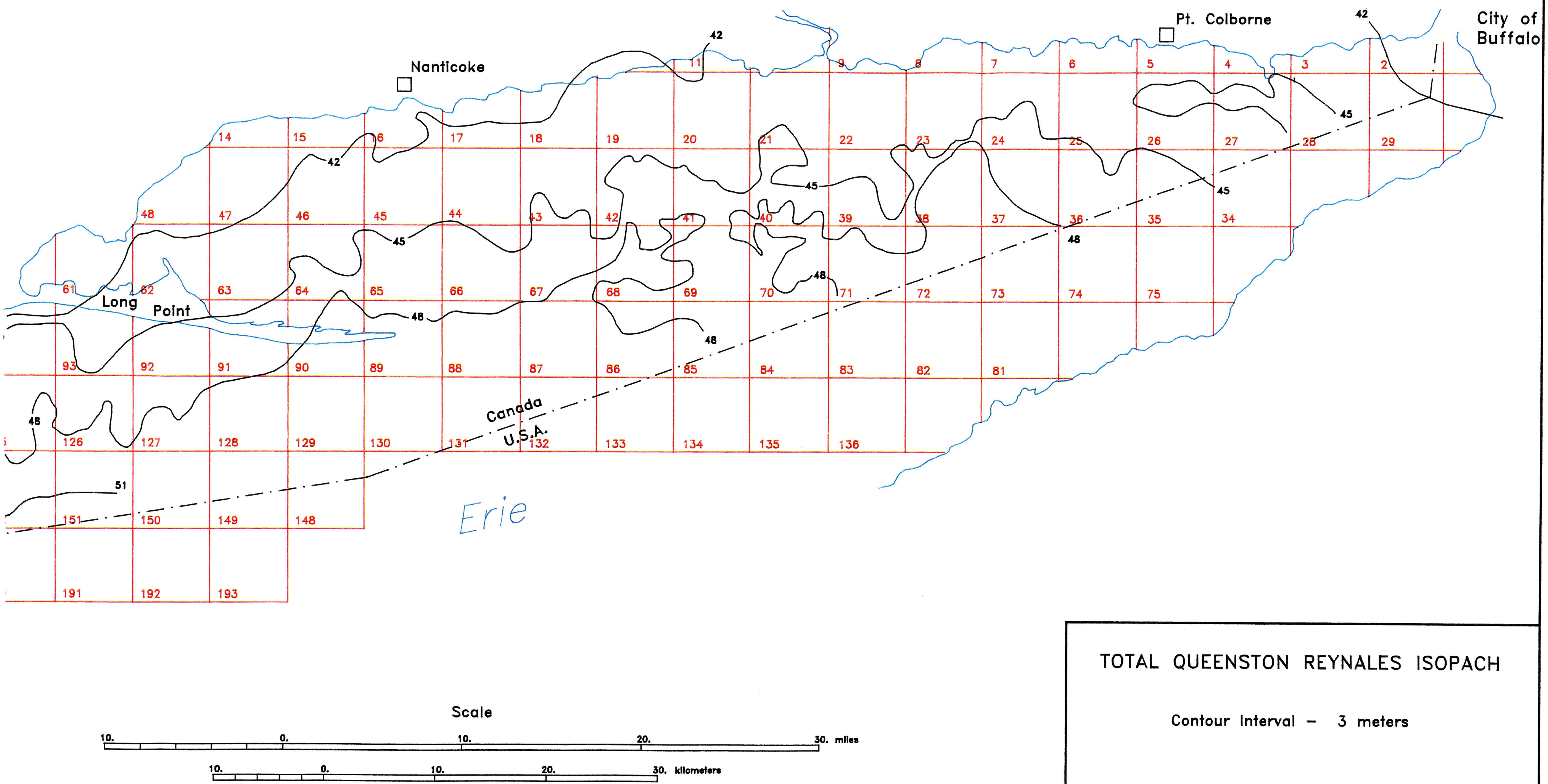
Contour Interval – 3 meters

Designed by: Tony Benincasa

Dept. Earth Sciences
Brock University

MAP 2


Pt. Stanley
Pt. Burwell
Rondeau Point
Lake



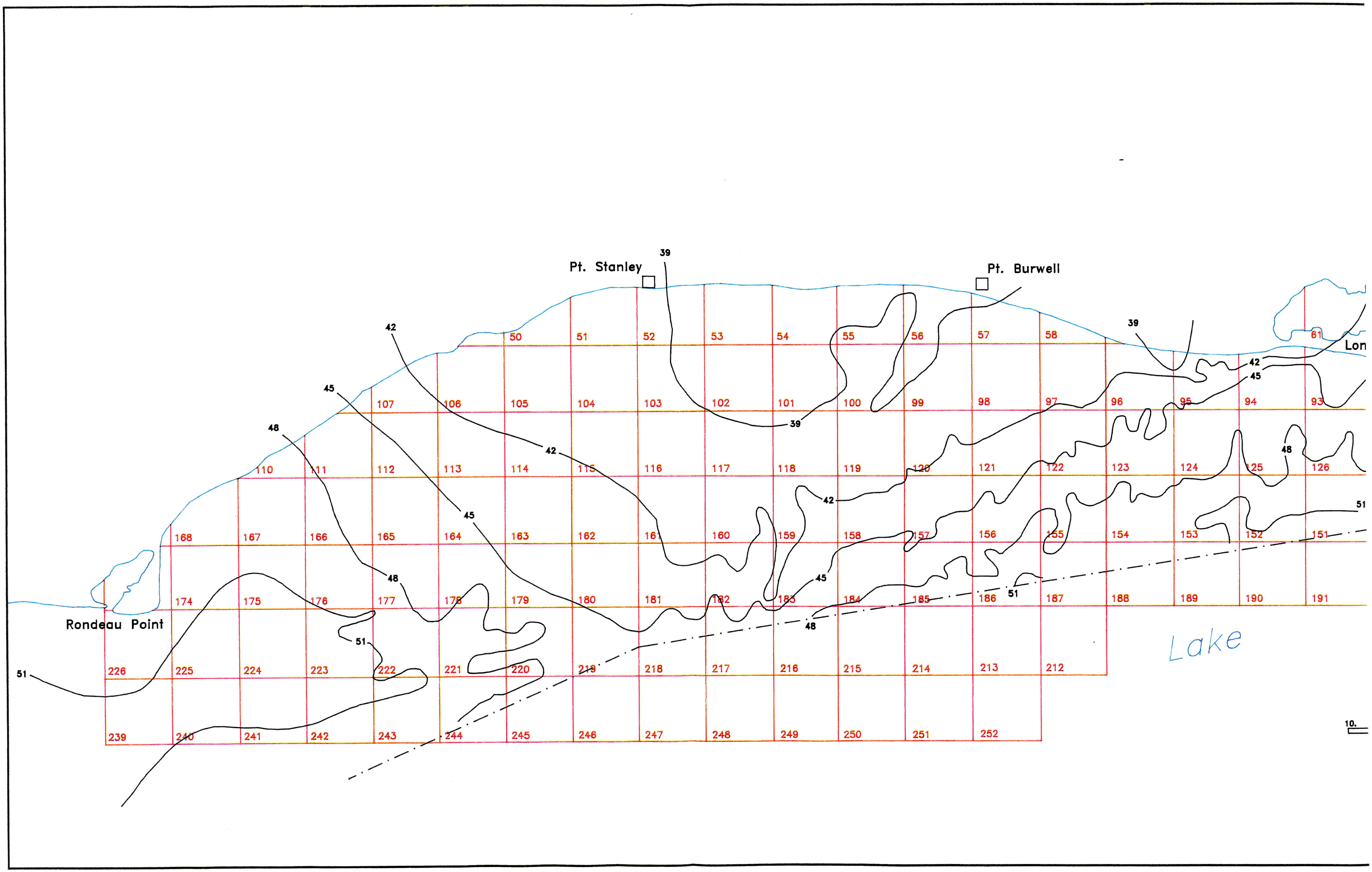
TOTAL QUEENSTON REYNALES ISOPACH

Contour Interval – 3 meters

Designed by: Tony Benincasa

Dept. Earth Sciences
Brock University

MAP 1


Pt. Stanley
Pt. Burwell
Rondeau Point
Lake
Lon
10.